LANDFILL GAS CONVERSION TO LNG and LCO₂

PHASE I FINAL REPORT Contract No 725089

For the Period
March 1998 - February 1999

prepared for

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February 25, 1998

*This work was performed under the auspices of U.S.D.O.E.

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EXECUTIVE SUMMARY

Process designs and economics were developed to produce LNG and liquid carbon dioxide (CO₂) from landfill gas (LFG) using the Acrion CO₂ wash process. The patented Acrion CO₂ wash process uses liquid CO₂ to absorb contaminants from the LFG. The process steps are compression, drying, CO₂ wash contaminant removal and CO₂ recovery, residual CO₂ removal and methane liquefaction. Three flowsheets were developed using different residual CO₂ removal schemes. These included physical solvent absorption (methanol), membranes and molecular sieves. The capital and operating costs of the flowsheets were very similar. The LNG production cost was around ten cents per gallon.

In parallel with process flowsheet development, the business aspects of an eventual commercial project have been explored. The process was found to have significant potential commercial application. The business plan effort investigated the economics of LNG transportation, fueling, vehicle conversion, and markets. The commercial value of liquid CO₂ was also investigated.

This Phase I work, March 1998 through February 1999, was funded under Brookhaven National laboratory contract 725089 under the research program entitled "*Liquefied Natural Gas as a Heavy Vehicle Fuel.*" The Phase II effort will develop flowsheets for the following: 1) CO₂ and pipeline gas production, with the pipeline methane being liquefied at a peak shaving site, 2) sewage digester gas as an alternate feedstock to LFG and 3) the use of mixed refrigerants for process cooling. Phase II will also study the modification of Acrion's process demonstration unit for the production of LNG and a market site for LNG production.

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A. INTRODUCTION

This report summarizes work completed during the Phase I period of March 1998 through February 1999 under contract 725089 entitled "Landfill Gas Conversion to LNG and Liquid CO₂." This Phase I research program was proposed and awarded under Brookhaven National laboratory RDP #723418 *"Liquefied Natural Gas as a Heavy Vehicle Fuel."*

The Phase I objective is to develop a process flow scheme for taking landfill gas to liquid methane and liquid CO₂ products. Process development includes pressure and temperature integration of Acrion's contaminant removal CO₂ wash technology with residual CO₂ removal and methane liquefaction. In parallel with process flowsheet development, the business aspects of an eventual commercial project have been explored.

This report is organized as follows. Section B reports progress on process flowsheet development. Three flowsheets were developed using three different residual CO₂ removal schemes. Major equipment was sized and power requirements were calculated. The economics of the schemes have been compared.

Section C reports efforts toward development of a business plan. The business plan effort investigated the economics of LNG transportation, LNG filling station operation, LNG vehicle conversion, and LNG markets. The commercial value of liquid CO₂ was also investigated. The commercial feasibility of the business plan model was studied, risk and opportunity scenarios were identified, and public policy considerations were addressed.

B. TASK 2 PROCESS FEASIBILITY STUDY

B.1 Introduction

The purpose of this task is to examine the feasibility of using municipal landfill gas as feedstock for the production of liquefied methane and liquid carbon dioxide. Municipal landfill gas (LFG) is a mixture of methane and carbon dioxide, roughly 50:50, and up to several thousand parts per million of troublesome contaminants. Reliable, economic removal of contaminants from LFG is a barrier to widespread utilization of LFG methane and carbon dioxide in most potential end markets.

Acrion has developed and patented technology [US Patent 5,681,360, Landfill Gas Recovery, 28 Oct 97] which removes contaminants from LFG and produces clean mixtures of methane and carbon dioxide suitable for processing to a variety of finished products. Acrion's contaminant removal technology integrated with conventional separation and liquefaction technology is examined for producing liquid methane and liquid carbon dioxide. The process receives about 4.35 million standard cubic feet per day (MMSCFD) of LFG, and produces liquid methane and liquid carbon dioxide. The landfill gas feed is characterized below in Table 1.

Table 1

Landfill Gas Feed Properties

Temperature, °F	70
Pressure, psia	14.7
Flow, lb-mole/hr (w/o water)	478.2
Methane	48.7%
Carbon Dioxide	47.8%
Nitrogen	0.9%
Water	saturated

The process has been modeled with the Hysim process simulator. A process description is given below; a schematic flow diagram is shown in Figure 1.

The process comprises three main sections: 1) contaminant and bulk carbon dioxide removal, 2) residual carbon dioxide removal to 50 ppm, and 3) methane liquefaction. In Section 1, contaminant and bulk CO₂ removal, raw landfill gas is compressed, dried, and cooled to condense a majority of the CO₂. A portion of the liquid CO₂ condensate is used to absorb chlorine and sulfur containing landfill gas contaminants; the remainder is food-grade liquid CO₂ product.

In Section 2, residual CO₂ is removed from a clean binary mixture of methane and CO₂

In Section 3, methane liquefaction, methane is condensed to produce liquid methane. Nitrogen contained in the feed LFG is separated from methane in this process section.

Product streams from the process are liquid methane, a methane rich fuel gas stream free of contaminants which is used for onsite power generation (not shown in Figure 1), food grade liquid CO₂, a stream containing all the landfill gas contaminants which is thermally oxidized in the landfill flare, and about 600 gallon/day of water condensate.

Process Flowsheets

Three process flowsheets were simulated. Two of the flowsheets use cold liquid methanol for residual CO₂ removal, and the other flowsheet uses a combination of a gas separation membrane and a molecular (mol) sieve bed for residual CO₂ removal. The first methanol flowsheet is described in Quarterly Progress Reports 1 and 2. The second methanol flowsheet is described in Quarterly Progress Report 3. The membrane and molecular sieve flowsheet is described below.

B.2 Membrane and Mol Sieve Residual CO₂ Removal Flowsheet

Process Description

Each of the three process sections is described in more detail below. All stream and equipment identifiers refer to detailed process flowsheets presented in Appendix A.

Section 1: Contaminant and Bulk CO₂ Removal Section

Process Sections 1 and 2 are shown in Figure A-1, Appendix A. Details of the compression and dehydration are shown in Figure A-2. Details of the contaminant and bulk CO₂ removal and CO₂ production process steps are shown in Figure A-3. Heat exchange details are shown in Figure A-4

Raw landfill gas (stream 99) is mixed with low pressure recycle gas, compressed, cooled to condense water, and dried over a molecular sieve bed. The dry gas (stream 108) is mixed with high pressure recycle gas, further compressed to 725 psia and cooled to the dew point of carbon dioxide (6°F) by heat exchange with product and recycle streams in HX104. The cold dry gas enters contaminant absorption column (abs 100) where it counter-currently contacts liquid carbon dioxide. Liquid CO₂ absorbs all the contaminants from the gas. Spent liquid CO₂ absorbent (stream 113) is partially vaporized to recover methane and CO₂ as high pressure recycle gas. The remaining contaminant rich liquid is vaporized and warmed to ambient temperature for cooling recovery and piped (stream 118) to the existing landfill gas flare where contaminants are thermally oxidized.

The contaminant-free gas leaving the top of contaminant absorption column (abs 100) is further cooled in exchanger qcond to condense carbon dioxide. This condensate is separated from the gas stream and returned to the top of contaminant absorption column (abs 100) as absorbent. Liquid carbon dioxide does not freeze at this temperature due to the presence of dissolved methane in the liquid. The contaminant-free gas (stream 124) from this condensation step contains 15% carbon dioxide, and is sent to process section 2, residual carbon dioxide removal.

A portion of the condensate liquid CO₂ (stream 122) is removed from near the top of the contaminant absorber (abs 100). Stream 122 is flashed to 250 psia and enters the top of

methane stripper (strip). Dissolved methane and nitrogen are stripped from the liquid CO₂ with reboiled vapor. Bottoms from the light ends stripper (stream 125) is food grade liquid CO₂ product. Vapor from the top of the stripper (stream 123) is combined with stream 120, contaminant recycle vapor, and is warmed by heat exchange with feed gas and recycled to the last stage of feed compression.

Section 2: Residual Carbon Dioxide Removal

Process Section 2 is shown in Figures A-1 and A-5, Appendix A.

Clean methane-CO₂ gas mixture (stream 124) is warmed before entering the gas separation membrane. The membrane product gas (stream 201) contains 2% CO₂ and the low pressure permeate gas (stream 202) contains approximately 50% CO₂. This permeate gas is recycled back to the landfill gas feed. The product gas enters a mol sieve bed where the remaining CO₂ is absorbed. The mol sieve product gas (stream 203) is cooled by heat exchange with the membrane feed gas, and is sent to the liquefaction (stream 300) section. The mol sieve is regenerated with low pressure purge vapor from liquefaction (stream 305b) which has been warmed by heat exchange with the membrane feed. This gas (stream 209) is heated during regeneration and is not heated during bed cooling. The regeneration product gas can be sent to gas engines to produce power to run process compressors and pumps. This engine fuel gas is free of trace contaminants and eliminates engine corrosion problems.

Section 3: Methane Liquefaction Section

In Section 3, methane liquefaction, methane is condensed to produce liquid methane. Process Section 3 is shown in Figure A-6, Appendix A. The methane is condensed (HX302) with ethylene refrigeration. It is subcooled with cooling supplied from vaporized liquid and warmed recycle gas in HX303. A portion of the subcooled liquid is depressurized, vaporized to supply cooling to HX303 and recompressed and recycled to the methane condenser. The remaining liquid is cooled by flashing the liquid down to near atmospheric pressure. There are two pressure reduction steps. A portion of the vapor from the first flash, which is enriched in nitrogen is used as regeneration gas for the mol sieve CO₂ removal step. Removing this gas prevents a buildup of nitrogen in the recycle loop. The remaining vapor and vapor from the second flash are recompressed and recycled to the methane condenser. These recycle vapor streams are warmed by heat exchange with the compressed recycle stream.

Process Energy Requirements

Power is required for LFG compression, refrigeration and methane recompression and pumping. Refrigeration is needed in feed gas cooling, CO₂ liquefaction, and methane liquefaction. The ethylene and propane cascade refrigeration system flowsheets are shown in Figures A-7 and A-8, Appendix A respectively. The heat exchange network for feed gas cooling and CO₂ condensation are shown in Figure A-4.

The energy requirements for LFG, propane, ethylene and methane compression and absorbent pumping are shown in Table 2. The total power requirement is 2751 Hp or 2057 kW. This power can either be purchased or a portion of it can be generated onsite from the contaminant free vent gas from mol sieve regeneration.

Equipment Size

Equipment sizes are shown in Table A-6 in the Appendix. LNG and Liquid CO₂ storage tanks were sized for a 3 day supply of product. Vessels and tower diameters were sized using the HYSIM process simulator. Heat transfer coefficients used in heat exchanger design were between 25 (low pressure gas) and 100 (boiling-condensing) BTU/hr/ft²/F°. Dehydration and CO₂ removal beds were designed for an 8 hour cycle time.

Process Economics

Tables 3 and 4 show estimated capital and annual operating costs and annual revenues for the process. Costs for membranes were estimated from a report on small scale CO₂ removal from natural gas [1]. In Table 3 electric power is purchased. In Table 4 a portion of the power is generated onsite using the contaminant free vent gas from the mol sieve regeneration. Product prices were \$0.40/gal for liquid methane and \$40/ton for liquid CO₂. The simple payback period for the purchased power case is 3.1 years. The simple payback with partial power generation is 3.0 years.

B.3 Process Comparisons

The three cases that were simulated are summarized in Table 5. The first case uses methanol to remove residual CO₂ and recover less CO₂ and LNG. The second case also uses methanol to remove residual CO₂. It recovers more CO₂ and LNG by recycling CO₂ and methane from the regeneration portion of the residual CO₂ removal step and concentrating the contaminants by vaporizing and recycling CO₂, to reduce the CO₂ loss in the contaminant stream. The third case also recovers greater products using the same recycling methods but uses a gas membrane and a molecular sieve to remove residual CO₂. The membrane is less selective than the methanol solvent for removing CO₂ so the amount of methane recycle is increased. This causes a greater power cost for case 3 over case 2. The capital cost for case 3 is slightly less than case 2.

For each of the three cases, electric power can be purchased or a portion of the power can be generated in an engine using a contaminant free mixture of nitrogen, methane, and carbon dioxide as fuel. This gas comes from the purge gas from LNG liquefaction and is used to regenerate the residual CO₂ removal step. At an electric cost of 0.05\$/Kw-hr, power production seems attractive.

Using a five year simple payback on capital, and a CO₂ credit of \$40/ton, the LNG production costs range from \$74 to \$98 per thousand gallons (7.4 to 9.8 cents/gal). With a \$20/ton CO₂ credit the LNG production cost are between \$98 and \$122 per thousand gallons (9.8 to 12.2 cents/gal). No costs for raw landfill gas were included in these calculations.

Table 2
Process Power Requirements
of Membrane and Mol Sieve Residual CO₂ Removal Flowsheet

	Horsepower	kW
LFG Compression		
Stage 1	533	
Stage 2	544	
Stage 3	618	
TOTAL	1695	1268
Propane Refrigeration		
Low Pressure	259	
High Pressure	324	
TOTAL	583	436
Ethylene Refrigeration		
Low Pressure	72	
High Pressure	179	
TOTAL	251	188
Methane Recompression		
Low Pressure	22	
Mid Pressure	48	
High Pressure	157	
TOTAL	221	165
Pumps		
CO ₂	1	
TOTAL	1	1
Total	2751	2057

Table 3
Capital, Operating Costs, and Revenues
Landfill Gas Recovery for LNG and CO2
Membrane and Mol Sieve Residual CO2 Removal

RAW LFG CONSUMPTION(dry)		4.36 MM SCFD;	50% CH4
OPERATING PARAMETERS			
Methane Recovery		83%	
CO2 Recovery		73%	
Onstream Factor, 350 days/year		96%	
PRODUCT		PRICE	
RLM		40 ¢/gallon	
Liquid CO2		40\$/Ton	
Power Required		2057 Kw	
CAPITAL COSTS		Installed	
Equipment		Cost	
Compressors		3,489,000	
Storage Tanks		606,000	
Columns		233,000	
Vessels		277,000	
Dehydration		191,000	
Heat Exchangers		1,462,000	
H2S Removal		169,000	
Membrane		300,000	
CO2 Adsorption Beds		427,000	
Pumps		51,000	
Capital Cost		7,205,000	
Contingency (18%)		1,297,000	
Total Capital Costs		8,502,000	
ANNUAL OPERATING EXPENSES			
Electric Power		0.05 \$/Kw-hr	863,940
SulfaTreat			10,933
Labor (\$12/hr, 2 operators/day)			67,000
Labor Overhead (100% of labor)			67,000
Maintenance Materials (2% of capital)			170,000
Maintenance Labor (3% of capital)			255,000
Taxes & Insurance (1.5% of capital)			128,000
Total Operating Costs			1,562,000
ANNUAL INCOME		Amount	Daily
RLM		21,500 GPD	8,600
CO2		90 TPD	3,608
Total Income			12,208
ANNUAL INCOME			Annual
RLM			3,010,000
CO2			1,263,000
Total Income			4,273,000
PAYBACK PERIOD		3.1 Years	ACRION TECHNOLOGIES

Table 4
Capital, Operating Costs, and Revenues
Landfill Gas Recovery for LNG and CO2
Membrane and Mol Sieve Residual CO2 Removal

RAW LFG CONSUMPTION(dry)		4.36 MM SCFD;	50% CH4
OPERATING PARAMETERS			
Methane Recovery		83%	
CO2 Recovery		73%	
Onstream Factor, 350 days/year		96%	
PRODUCT	PRICE		
RLM	40 ¢/gallon		
Liquid CO2	40\$/Ton		
Power Required	2057 Kw		
Power Generated	1136 Kw	from Clean LFG	
CAPITAL COSTS		Installed	
Equipment		Cost	
Compressors		3,489,000	
Storage Tanks		606,000	
Columns		233,000	
Vessels		277,000	
Dehydration		191,000	
Heat Exchangers		1,462,000	
H2S Removal		169,000	
Membrane		300,000	
CO2 Adsorption Beds		427,000	
Power Generation		643,000	
Pumps		51,000	
Capital Cost		7,848,000	
Contingency (18%)		1,413,000	
Total Capital Costs		9,261,000	
ANNUAL OPERATING EXPENSES			
Electric Power	0.05 \$/Kw-hr	386,820	
SulfaTreat		10,933	
Labor (\$12/hr, 2 operators/day)		67,000	
Labor Overhead (100% of labor)		67,000	
Maintenance Materials (2% of capital)		185,000	
Maintenance Labor (3% of capital)		278,000	
Taxes & Insurance (1.5% of capital)		139,000	
Total Operating Costs		1,134,000	
ANNUAL INCOME		Amount	Daily
RLM	21,500 GPD	8,600	3,010,000
CO2	90 TPD	3,608	1,263,000
Total Income		12,208	4,273,000
PAYBACK PERIOD	3.0 Years	ACRION TECHNOLOGIES	

Table 5
Process Comparisons

Residual CO ₂ Removal		Case 1 MeOH Wash		Case 2 MeOH Wash		Case 3 Membrane/ Mol Sieve	
Production							
LNG	KGal/day	19		21.5		21.5	
CO ₂	Tons/day	65		90		90	
Power Generation		no	yes	no	yes	no	yes
Purchased Power	Kw	1686	0	1941	805	2057	921
Capital Cost	K\$	7220	8184	8540	9294	8500	9261
Operating Cost *	K\$/yr	1322	678	1515	1087	1562	1134
LNG Production Cost @	\$/KGal	97.7	73.9	91.3	78.4	93.1	80.3

* Electric Power at 0.05\$/Kw-hr

@ Byproduct Credit for CO₂ at 40\$/ton,
5 yr Payback on Capital, 350 days/yr Operation

References

1. Changela, M.K and Reading, G.J, Evaluation of Process Costs for Small Scale - Carbon Dioxide Removal from Natural Gas, Topical Report, M.W. Kellogg, for the Gas Research Institute (GRI-91/0056), Chicago IL, August 1991.

C. TASK 3 BUSINESS PLAN DEVELOPMENT

The objective of this task is to identify and provide an analysis of the conditions under which LFG is appropriate for conversion to LNG for use as a vehicle fuel, using the Acion technology. Having identified these conditions, it is then possible to formulate plans to optimize these conditions in order to encourage a greater number of fleet owners to convert to LNG as their fuel of choice for heavy vehicles.

Documentation on the use of natural gas as a vehicle fuel is abundant; however, in the course of gathering facts on the subject, we have been able to update findings regarding the technology and the relevant commercial feasibility required to convert LFG to vehicle fuel and to operate vehicles using LNG as the primary fuel.

Task Summary

Overview

After careful analysis of the available facts, it has been determined that the conversion of Landfill Gas (LFG) to Liquid Natural Gas (LNG) for use in heavy transportation vehicles such as Class 7 and 8 trucks¹, municipal buses, and railroad locomotives has significant potential commercial application if one or two obstacles can be overcome. Those obstacles are: 1, lack of a national network of LNG fueling stations; and 2, the cost of delivering the LNG to refueling stations.

Using the Acion process, the conversion of LFG to LNG and carbon dioxide (CO₂) is cost effective for municipalities or other government developers, and could be practical for some private commercial enterprises. Municipalities could reap significant economic and other benefits by installing and operating an LFG separation and cleaning plant using the Acion process. Private commercial enterprises do not have the same access to low cost funds as municipal governments and they are required to pay taxes which may initially be a barrier to private investment. It is, however, believed that the process will be more financially attractive for private enterprise after the technology has been successfully demonstrated on a full commercial scale.

Conversion of LFG to LNG and CO₂

The Acion process has been very successfully demonstrated on a pilot plant level. The conversion of LFG using the Acion process can produce LNG (99.85% pure CH₄) and CO₂ (food grade) in a cost effective manner, if both can be sold at current market prices. Both products should be sold to generate sufficient revenue to make the process commercially viable.

Commercial Value of LNG and CO₂

LIQUID NATURAL GAS: The LNG produced by the Acion process is exceptionally marketable because it is expected that the LNG will be 99.85% pure methane. The value of the purity level is important because it has a known and constant chemical composition and because it is less susceptible to the chemical process known as *weathering*.² The market price of LNG has been fairly constant and predictable over time and as a vehicle fuel it is taxed at a slight advantage to Diesel fuel.

CARBON DIOXIDE: The marketability of CO₂ is highly dependent on geography. In those areas of the United States which have a demand without a corresponding supply, CO₂ can be sold to distributors, such as *Praxair*, for between \$30.00 and \$35.00 per ton at the time this report is written (December 1998). One other marketing factor is the possible negative perception of CO₂ produced from landfill gas being used in the food processing industry.

Fueling Technology

The technology for manufacturing, installing, and operating LNG fueling stations for trucks has progressed to the point where there is little difference between fueling a Diesel powered vehicle and an LNG powered vehicle. The cost effectiveness of the fueling station will depend on several variables including: the number and fuel capacity of the trucks or buses fueling each day as well as, the local regulations which may demand compliance and/or mandate additional construction, maintenance, and operating costs.

Fueling Logistics

There is currently no national or even regional network of LNG fueling stations, public or private. Therefore, trucks and buses are limited to routes which will permit refueling. This normally means that a route or operating area must permit the vehicle to return to the same fueling station it needs to refill. A municipal bus route and some truck delivery areas are compatible with this limitation. Most inter-city or long haul truck or bus operation is excluded on a practical basis from the use of LNG as a primary fuel. This lack of a network of LNG refueling locations is the single largest obstacle to converting a substantial number of road vehicles to LNG as the primary fuel.

Commercial Feasibility of LNG Engines

Most of the major manufacturers of Diesel engines are developing engines to run on LNG. The cost of the engines is still higher than those that run on diesel fuel, however, if LNG becomes a significant primary fuel, economies of scale will begin to apply to the cost of manufacturing. The cost differential has already been reduced by approximately 50% over the past year on some types of LNG engines.

At least in the laboratory, it has been demonstrated that the thermal efficiency of dual fuel LNG engines and conventional Diesel engines is roughly equal. The operating characteristics and load hauling ability of dual fuel LNG engines is today roughly on a par with Diesel engines. Some maintenance costs have been reduced by 50% to 75% of the same maintenance costs for conventional Diesel engines. The potentially significantly reduced cost of maintenance is a major advantage in favor of the dual fuel LNG engines.

Practical Aspects of LNG as a Transportation Fuel

All other things being equal, LNG is, in economic terms, an ideal alternative transportation fuel. It is readily available in many parts of the country and could be more universally available if the demand warranted. The cost of LNG on a FOB basis has been, historically, stable and one of the lowest cost per BTU hydrocarbon sources of energy. It burns cleanly and produces relatively little environmental pollution.

LNG offers a higher energy concentration per cubic measure than CNG which means smaller tank size and/or greater travel range for the LNG powered vehicle. For a vehicle

which travels on a regular and frequent basis, LNG is generally the better choice for an alternative fuel.

Methods to Increase the Conversion of LFG to Usable Products

Natural market forces could cause fleet operators and other heavy vehicle owners to move to the use of LNG as a primary transportation fuel if it is readily available at a cost equivalent to the use of Diesel.

Because of relatively consistent low market prices and abundant domestic supplies of LNG, vehicle owners can plan for fuel costs and not be concerned about supply interruptions by foreign producers. Although the costs of the LNG engines are higher than Diesel, the costs are dropping and the reduced maintenance costs can be balanced against the higher engine costs.

In subtask 3.9, Public Policy Considerations, one scenario is detailed that suggests a low cost method to establish regional networks of LNG refueling stations using existing truck stops along high traffic corridors to provide a means for fleet operators to refuel trucks on long distance routes. It is suggested that the Federal government underwrite the initial construction of the LNG refueling stations at existing truck stops and then sell the equipment to the truck stop owner when the demand for LNG as a fuel increases. There should initially be an assured supply of LNG fuel equal to the expected life of the LNG vehicles.

In order to supply LNG at the least possible cost to the refueling stations, the conversion of LFG to LNG from nearby landfills using the Acion process would be a part of the overall plan. Involvement by the Federal government would be limited to assisting municipal governments construct the LFG conversion plants.

Task Organization

This task develops a business plan which includes three business models (one each for three different sizes of Landfill Gas Recovery facilities) to predict costs, revenue, and economic feasibility of converting landfill gas to LNG and LCO₂. The proposed use of the LNG examined in these models will be to power transportation, including class 7 and class 8 trucks and buses, and railroad locomotives.

DETAILED SUMMARY OF THE SUBTASKS: The details supporting the conclusions for Task 3 are provided in the following subtasks summaries:

- C.1. Establish the Scale of the Business Plan Model
- C.2. Determine the Economics of Transporting LNG
- C.3. Determine the Economics of Operating an LNG Filling Station
- C.4. Determine the Commercial Feasibility of Purchasing, Converting, and Operating Vehicles with LNG
- C.5. Identify Current and Potential Markets for use of LNG as a Transportation Fuel
- C.6. Determine the Commercial Value of LCO₂

C.7. Determine which, if any, Models are Commercially Feasible

C.8. Identify Possible Future Risk and Opportunity Scenarios

C.9. Public Policy Considerations

REFERENCES: References and background information to support the findings written in the Executive Summary are provided in endnotes to this section of the report.

ATTACHMENTS: Attachments of supporting reports and data collected can be found in Appendix B. A list of attachments is included at the beginning of the Appendix

C.1. Subtask 3.1 Establish the Scale of the Business Plan Model

Extraction of the Landfill Gas

For the purpose of these business models, it has been assumed that landfills will already have in place a gas collection system to collect the LFG which has been created by the decomposition of the landfill refuse³. The grid will collect the gas and take it to one or more locations at the landfill to be burned or to be connected to some other means for disposition of the gas.

In as much as the LFG collection grid has been mandated, there is no additional marginal cost required to collect and extract the LFG from the landfill in order to provide LFG to a Landfill Gas Recovery facility; no cost of collection or extraction of the LFG from the landfill is included in these models.

Terms of Sale for RLM and LCO₂

Both the methane and the carbon dioxide will be stored as liquids in appropriate tanks on the landfill. For the purpose of these models, it is assumed that the LNG (RLM) and LCO₂ will be sold on an "FOB, the landfill" basis where the buyer will take possession of the liquid gases at the storage tanks. The landfill gas recovery facility operator will only be responsible for making the liquid gases available to the buyer at the storage tanks.

Conversion and Separation Plant

Three Landfill Gas Recovery facility sizes were chosen. The LFG processing capacities of the model facilities are:

2.0 Million SCFD (Standard Cubic Feet per Day)

3.5 Million SCFD

5.0 Million SCFD

The operating parameters and summary costs are listed below; additional details may be found in Appendix B.

3.5 Million Standard Cubic Feet per Day Landfill Gas Recovery Facility Model

LFG Input Requirements¹⁰:

Raw LFG Consumption (dry):	3.50 million SCFD
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Operating Standards¹¹:

Methane Recovery:	73%
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CO ₂ Recovery	52%
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Plant operation (350 days per year) ¹²	96%
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Production Capacity

Refrigerated Liquid Methane	15,300 gallons per day
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Carbon Dioxide	52 tons per day
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Facility which purchases electricity for operation¹³:

Estimated Cost of Constructing Facility:	\$ 6.3 million
--	----------------

Estimated Annual Operating Expenses ¹⁴ :	\$ 1.1 million
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Estimated Annual Revenue Produced	\$ 2.3 million
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Facility which generates its own electricity for operation:

Estimated Cost of Constructing Facility:	\$ 7.2 million
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Estimated Annual Operating Expenses ¹⁵ :	\$ 0.6 million
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Estimated Annual Revenue Produced	\$ 2.3 million
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* Refrigerated Liquid Methane (RLM) = Liquid Natural Gas (LNG)

5.0 Million Cubic Feet per Day Landfill Gas Recovery Facility Model**LFG Input Requirements¹⁶:**

Raw LFG Consumption (dry):	5.00 million SCFD
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Operating Standards¹⁷:

Methane Recovery:	73%
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CO ₂ Recovery	52%
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Plant operation (350 days per year) ¹⁸	96%
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Production Capacity

Refrigerated Liquid Methane	21,800 gallons per day
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Carbon Dioxide	74 tons per day
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Facility which purchases electricity for operation¹⁹:

Estimated Cost of Constructing Facility:	\$ 7.8 million
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Estimated Annual Operating Expenses ²⁰ :	\$ 1.5 million
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Estimated Annual Revenue Produced	\$ 3.3 million
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Facility which generates its own electricity for operation:

Estimated Cost of Constructing Facility:	\$ 8.9 million
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Estimated Annual Operating Expenses ²¹ :	\$ 0.7 million
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Estimated Annual Revenue Produced	\$ 3.3 million
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* Refrigerated Liquid Methane (RLM) = Liquid Natural Gas (LNG)

C.2. Subtask 3.2 Determine the Economics of Transporting LNG

The cost of using a common carrier to transport LNG in 10,000 gallon tank trailers has been determined to be approximately \$ 0.03 to \$ 0.04 per LNG gallon per 100 miles of transport.²² The cost will obviously vary depending on the length and location of the route traveled.

C.3. Subtask 3.3 Determine the Economics of Operating an LNG Filling Station

Refueling a vehicle with LNG is now about as safe and simple as refueling a vehicle with gasoline or diesel fuel.

There is a public refueling facility at a convenience store in Bloomfield, New Mexico and a number of private facilities for fleet operations around the country. In order to refuel a vehicle several criteria must be met. The dispensing system must:

1. be simple to operate and take no more time to fill than conventional fuel.
2. be safe for the driver (or fueling attendant), the vehicle being refueled, any other people or equipment in the area, and the environment.
3. have a connector (nozzle) that is compatible with the connector (opening) on the fuel tank on the vehicle.
4. able to refuel a tank that may have a high internal pressure or an ambient pressure of one atmosphere.
5. be able to refuel a vehicle with a tank that is either empty or nearly full.
6. be able to fuel a vehicle tank with a cryogenic temperature or a tank with a temperature equal to the ambient air.
7. be able to collect and report the amount of fuel dispensed by the driver and vehicle.
8. be roughly as simple for the station owner/operator to maintain as a Diesel or gasoline refueling system.

There are systems currently available and operating that meet most of these requirements. LNG refueling systems operating today are very similar to conventional gasoline and Diesel pumps and can dispense up to 50 gallons per minute. Fuel will not flow unless a leak-proof connection is made which reduces the possibility that a driver can be injured by the cryogenic liquid. Most people refueling vehicles do, however, wear a clear plastic face mask or shield, and heavy work gloves, both common while Diesel refueling for added safety. In addition, a safety emergency shutoff switch is located on the pump as is the case with many conventional fueling operations.

Most fueling stations use a single hose to both move the LNG into the vehicle tank and to remove the excess methane gas from the tank. The excess gas can be either recycled back

to the LNG storage tank, vented to the atmosphere, or placed into a natural gas pipeline and sold to a natural gas utility company. Since the methane has an economic value and an energy content, it normally makes sense to recycle it either back into the tank or into a pipeline. Removing the excess gas from the vehicle tank being refueled eliminates any problems that could be caused in the refueling process by having a high internal pressure in the vehicle fuel tank.

The fueling system must be able to "cool down" an empty tank so that the LNG remains in a liquid form. It must also be able to detect when a tank is full and automatically stop the filling process. Dispensing systems capable of these activities are operating today including at the Bloomfield, NM, LNG self-service facility.

LNG fueling systems that can use a card reader to identify a driver and/or vehicle, record the fuel dispensed and report this data for invoicing or fuel consumption records, are available and in use just as it is for gasoline and Diesel facilities.

There are four major hurdles to an ideal LNG fueling system which have not yet been crossed. They are:

1. There is no standardization of fuel composition. The BTU content, percent of methane, and percent of other chemicals can vary drastically. For maximum fuel efficiency, minimum vehicle maintenance, and maximum engine service life, a fuel as close to pure methane as possible seems to be the most desirable.²³
2. There is no standard nozzle or connector type. This means that only vehicles with compatible tank connectors can use a particular LNG fueling station. If there is a fueling station that is only serving a private fleet, there is no problem, however, this lack of standards remains a challenge to be met for a vehicle owner that may be contemplating conversion to an alternative fuel. It also reduces the number of potential customers for a public fueling station.
3. Because some of the parts (especially the fueling hose to vehicle tank connectors) used in assembling the LNG fueling stations are made to order, the number of maintenance parts that must be stocked or the lead time to reorder can be a problem for the fueling facility owner/operator. One operator of a LNG fueling facility for a private fleet said that his only maintenance problem was the nozzle; in fact, the time the manufacturer took to repair or replace the nozzle connector was taking increasing longer and was less cooperative about permitting the facility operator to do minor repairs. This operator owned two nozzles; one for use and one to be in route between the fueling facility and the nozzle manufacturer.²⁴
4. There is no consistent network of LNG fueling stations across the country or even within geographic regions. A vehicle owner operator is limited to travel a distance that permits coming back to the refueling point on a single tank of LNG. This lack of long range mobility will significantly reduce the number of LNG fueled vehicles.

Another consideration that the potential investor in a LNG fueling facility must consider is how large should the initial storage tank be for the LNG. The LNG storage tank is one of the more expensive parts of the facility. Initially installing a tank to satisfy the maximum anticipated fueling requirements can cause the initial investment to increase substantially.

Storage capacity for cryogenic fluids poses some challenges that are not present with gases or non-cryogenic liquids. A cryogenic fluid can not reside indefinitely in a storage facility. It will absorb heat and turn to a gas. Pressure from the gas will build and eventually excess gas will have to be removed from the tank. This normally means wasted fuel. For the facility owner it would be like purchasing gasoline and then storing it in open vats. The gasoline would soon evaporate and the amount available for sale would be considerably less than what was initially purchased for inventory. A partially full storage tank will convert the remaining cryogenic fluid to a gas faster than a full tank just as your food freezer stays colder, longer if it is full than if it has only a small amount of the capacity filled. Therefore, leaving a tank partially empty for a long period will hasten the evaporation process. It is better to have a tank that requires refilling frequently.

One fueling facility visited for this report had an on site 13,000 gallon LNG storage tank which was refilled every six weeks. A very large amount of the LNG that was placed in the storage tank evaporated to gas before it could be used in the truck fleet. This loss of fuel dramatically increased the LNG fuel costs for the fleet. Some of the cost of the gas was, however, recovered by selling it to a natural gas pipeline operator.²⁵

A second situation arises from the fact that LNG is not just Methane but is a mixture of chemicals. A process known as *weathering* takes place where certain chemicals turn to gas before others. The chemicals that turn to gas first will be the first to be removed from the tank. The amounts of the chemicals that remain in the cryogenic fluid will change as a percentage of the remaining liquid. (This process is similar to the evaporation of salt water. As the water evaporates, the salinity of the remaining liquid increases.)

The BTU content and amount of undesirable chemicals in the LNG will change. The problem of *weathering* is reduced as the purity of the LNG increases. The Acron process produces LNG with a 99.85% methane content; therefore, a change in chemical composition is not as significant a concern.

An average LNG tank trailer holds approximately 10,000 gallons. To avoid having to empty a storage tank at a refueling facility, the tank should hold something more than 10,000 gallons (perhaps 12,000 to 15,000 gallons.) However, this may be too large for initial consumption. Smaller tanks are available, however, there will be an increased cost of LNG on a per gallon basis to purchase less than a full tank trailer load at a time. In addition, there will be costs each time a smaller tank is replaced with a larger tank as refueling requirements grow.

A rough estimated cost of a "standard" self-serve LNG fueling station is \$400,000 to \$425,000²⁶. This type of facility would include a 13,000 gallon cryogenic storage tank, pumps, conditioner/heater to increase pressure in the vehicle fuel tank, a control system, safety systems and one self-serve 25 to 40 gallon per minute dispenser equipped to fuel one heavy duty vehicle at a time, with card reader and record keeping system.²⁷

An alternative concept in refueling LNG vehicles does not use a main storage tank. This style of LNG fueling takes a natural gas feed stock made up of approximately 95% methane, removes moisture, CO₂, and the material that gives natural gas its distinctive smell. It then liquefies the remaining material to create LNG. This type of fueling facility costs between \$500,000 and \$600,000 plus the costs of a general contractor, permits, and site preparation. The facility is designed to provide a 1,000 Diesel equivalent gallon²⁸ per day LNG fueling capacity. The estimated cost of a Diesel equivalent gallon of LNG is in the range of \$0.80 to \$0.85 plus applicable Federal and state taxes.²⁹

C.4. Subtask 3.4 Determine the Commercial Feasibility of Purchasing, Converting, and Operating Vehicles with LNG

There are three primary forms of transportation that will be reviewed: class 7 and 8 trucks³⁰, municipal buses, and railroad locomotives. Each form of transportation will be reviewed by itself in terms of capital investment costs and operating costs.

While there is a great deal of valuable data available from many sources, and hundreds of pages of data were reviewed, there were two sources of information that were most helpful: Dr. John Beck of the Clean Air Partnership in San Diego, California and Dr. John Barclay of the University of Victoria, British Columbia, Canada.

To present hard comparative data on costs or operating efficiencies poses two challenges: one, the variables are so great as to require so narrow a specific situation as to be less than useful to extrapolate into policy; and two, the dynamics of the situation are changing so quickly that what was correct a few months ago is no longer correct today, and what is correct today, will not be correct a few months into the future. Therefore, this section will deal more with meaningful trends than with current data which can quickly become obsolescent.

To provide some understanding of the speed with which the dynamics of the issue is changing, Appendix B contains two documents produced by CALSTAT and copyrighted in 1996 on the *Regulatory barriers and Opportunities* and the *Market Barriers & Opportunities*. Many of the problems that existed when these two reports were written are now moot.

There are two basic designs for large LNG engines. One is a dual fuel Diesel compression style which uses Diesel fuel to start, and when under load, switches to LNG. The other engine is a spark ignited LNG only engine with a throttle.

Class 7 and 8 Trucks and Municipal Buses

There are two ways that Class 7 and 8 trucks can run on LNG instead of Diesel. The first is to convert existing trucks from Diesel to LNG, however, the second, purchase of trucks with engines designed to operate on LNG, is now available from most of the major manufacturers of Diesel engines. None of the engines designed specifically to operate on LNG are believed to be in assembly line production as this report is being written (December 98).

According to Dr. Beck, the dual fuel Diesel-type compression engine will achieve thermal efficiency parity with the Diesel-only engine at about 40 to 44% in Class 6, 7 and 8 engines. This thermal efficiency parity will hold true for municipal busses as well as trucks.

The spark ignited throttle style of LNG engine gains in thermal efficiency as the load on the engine increases from idle to full load, however, it never reached full parity. The efficiencies found in Dr. Beck's laboratory were:

Idle	2 x the energy consumption of a Diesel engine
Half Load	1.3 x the energy consumption of a Diesel engine
Full Load	1.15 x the energy consumption of a Diesel engine

If the dual fuel LNG engine runs at thermal efficiency parity with the Diesel-only engine, what are the comparative advantages and disadvantages of the two engines?

Cost of the Engines: The installed cost of the dual fuel engine is currently 40% more expensive than Diesel. About half of this cost is the cryogenic fuel tank. This cost estimate example is for the Clean Air Partnership to convert a Caterpillar Diesel engine to dual fuel use.

Westport Innovations Inc. of Vancouver, British Columbia, Canada offers a conversion kit for municipal busses for about \$20,000.

The initial investment cost advantage favors the Diesel engine. However, Dr. Beck estimates that the cost of the dual fuel engine will continue to decline. Dr. Barclay and Dr. Beck both confirmed that the cost differential of the LNG engines over the Diesel engines has been reduced by about half over the past year and both view similar cost reductions to continue. Dr. Beck is particularly optimistic, finding that the primary cause for most of the current cost differential would be eliminated when the conversions go into full production and the inherent economies of scale can be realized.

Offsetting some or all of the initial investment cost differences have been subsidies in the form of tax credits and other incentives from the Federal and some state governments.

Maintenance Costs: Dr. Beck's research indicates that parts wear out on the dual fuel engines at about 25% the rate of the Diesel engine; furthermore, the oil might never need to be changed. The reason cited for this significant reduction in maintenance requirements is the cleanliness or purity of the LNG fuel.

Service Life of the Engine: The service life of the dual fuel engine is expected to be 2 to 4 times that of its Diesel counterpart. While this sounds attractive, the economic reality is a bit more subdued. An engine that has a designed service life of 700,000 miles increased that to 1.4 million miles does not have significant value to the owner if the rest of the vehicle has exceeded its useful life.

Fuel Costs and Availability: This is the area where LNG does not have any advantages. In order for LNG to be cost competitive in today's market, it must be

readily available at a delivered cost of about \$0.40 per gallon plus applicable Federal and State taxes. Transportation costs for LNG in a 10,000 gallon tank trailer average about \$ 0.03 to \$ 0.04 per gallon per 100 miles traveled.

Only one public LNG fueling station was found in Bloomfield, New Mexico. Other LNG fueling locations are operated by fleet operators. The lack of a network for refueling with LNG is one of the biggest impediments to conversion. A list of some of the possible LNG refueling points is included in Appendix B. It should be noted that most of these locations are private and the connectors between the fueling point and vehicle may not be compatible.

One positive note has been a change in the Federal excise tax on LNG as a motor fuel. In the past there has been a tax disadvantage to LNG. Today the tax on one gallon of LNG is 11.9 cents. Because a gallon of Diesel fuel has about 1.68 times as much energy as a gallon of LNG, the effective Federal tax on the LNG equivalent to the energy in a gallon of Diesel (Diesel Equivalent Gallon) is a about 20 cents per Diesel Equivalent Gallon. This favors the LNG by a few cents per Diesel Equivalent Gallon.

In Canada there is no specific Federal excise tax on LNG as a motor fuel, however, there are other taxes including the national Goods and Services Taxes (GST), a form of national sales tax or Value Added Tax.

Environmental Factors: The dual fuel LNG engines produce about half the pollution of a Diesel engine.

Manufacturers of engines and vehicles designed to operate on LNG are listed in Appendix B.

Railroad Locomotives

Tests of LNG as a fuel for use in railroad locomotives has been conducted by both Burlington Northern, the largest private consumer of Diesel fuel in the United States, and Union Pacific, the second largest private user of the fuel. Union Pacific consumes about 1.5 million gallons of Diesel each day.³¹

The railroads' interest in LNG focuses on three goals:

1. They need an assured supply of fuel
2. They need a predictable price for fuel
3. They need to be prepared for environmental restrictions

LNG has the potential of meeting the three goals outlined above.

Fuel Supply: With Union Pacific consuming about 1.5 million gallons of Diesel fuel per day and Burlington Northern consuming even more, the railroads need to know that they will have a supply of fuel that will not be threatened by OPEC oil embargoes or other interruptions to the supply chain. Natural gas is in plentiful supply both in the United States and in other parts of the world. A switch to a fuel made from natural gas eliminates the risks of interruptions to fuel supplies. LNG makes more sense than CNG because of the huge quantities consumed by each engine, the distances traveled between refueling,

and the ability to store more energy in a smaller volume with LNG than CNG.

Fuel Prices: Natural gas has a history of relatively stable and predictable prices compared to Diesel fuel or other fuels made from crude oil. In addition, natural gas has a history of a high BTU to cost ratio making it a relatively low cost source of energy.

Environment Concerns: LNG generally provides less pollution than diesel fuel for the same amount of work performed. Other alternatives to reduce pollution may not provide as significant a reduction. One consideration is changing to all electric locomotives.

The Southern California Regional Rail Authority (SCRRA) examined conversion of its commuter rail services to meet Federally mandated clean air standards in a cost effective way. The Authority found that a change to electricity would both be extremely expensive and probably not reach their goals.

SCRRA determined that a conversion to electricity would:³²

- Cost 4.6 billion dollars
- Take 18 years to complete
- Only achieve a 76% reduction in NOx

At the same time SCRRA determined that a conversion to LNG would:

- Cost tens of millions not billions for the capital cost of LNG Locomotives
- Take only a few years to complete
- Achieve 70 to 80% reduction in NOx

One consideration in the electrification / pollution reduction equation is how is the electricity going to be generated. If the power is generated from a traditional fossil fuel burning plant, the production of pollution is transferred from the locomotive to the power generation plant and energy is lost by the attenuation caused by the power lines required to get the energy from where it is produced to where it is needed.

If the electricity is produced by nuclear or hydroelectric facilities other environmental impacts and costs must be considered.

Manufacturers of LNG Powered Vehicles

Lists of some of the manufacturers of engines and vehicles designed to operate on LNG are included in Appendix B

C.5. Subtask 3.5 Identify Current and Potential Markets for use of LNG as a Transportation Fuel

For LNG to be an effective alternative fuel, several conditions need to be met. Vehicle operations which meet these criteria are candidates for LNG fuel. The criteria currently are:

Vehicle size: Large vehicles such as Class 7 and 8, municipal busses, railroad locomotives, and boats such as ferry boats which would normally use Diesel are prime candidates.

Frequency of Operation: Vehicles that are used on a continuous or predictable basis are better candidates for LNG. The LNG fuel does not store well in the vehicle fuel tank. As the LNG resides in the vehicle's tank, it will absorb heat and the cryogenic fluid will turn to gas. If the engine is operating, the gaseous fuel will be burned in the engine. If, however, the engine is not running the pressure will build, and the gas will be vented to the atmosphere - a waste of fuel since it is not consumed to perform work.

Proximity to Refueling Facilities: The vehicles must be operated in an area where they can be refueled. In most cases, this means that the vehicle must return to the same refueling location; therefore, the operating range is no greater than the distance that can be covered in a round trip on one tank of fuel.

Type of operation: The preferred type of operation for maximum comparative fuel efficiency is one that calls for the least amount of idle time, and the maximum amount of time working at full load.

Vehicle operations which fall within the first three of these parameters include:

Municipal Busses that can return to their refueling points before the fuel in the tanks is completely consumed.

Class 7 and 8 trucks that operate in a range that allows them to return to their refueling points before the fuel in the tanks is completely consumed. It should also be noted that Dr. Beck at the Clean Air Partnership has indicated that class 6 trucks can also be good candidates for conversion to LNG.

Railroad locomotives that operate on specific routes where there is sufficient fuel onboard the train to make a round trip or where refueling points have been established to permit the train to refuel before the LNG is entirely consumed.

Boats such as ferry boats that follow the same course, and where a refueling point can be established at one or more of the destinations on the course.

Non-Transportation applications include the use of LNG to fuel electricity generation equipment and *peak shaving*. *Peak shaving* is the practice of storing LNG for use in natural gas pipe lines when the normal supply of gas is not sufficient to meet demand.

C.6. Subtask 3.6. Determine the Commercial Value of LCO₂

Liquid Carbon dioxide (LCO₂) is, in most markets, sold by manufacturers on a wholesale basis through a few major distributors. Most geographic markets have a very few major distributors to whom a producer can sell. The current market conditions are generally stable resulting from prices and a market willing to buy at the market price, if there is not already a sufficient supply. The price currently being paid in parts of the country where there is not already sufficient supply is between \$30.00 and \$35.00 per ton.³³

If there is already a sufficient supply, the major distributors would not be interested in purchasing from new manufacturers.

Wholesale markets are regional. Regional boundaries are determined by transit distance between manufacturer and end user. In the Western part of the United States, there is generally more supply than demand. On the other hand, the LCO₂ could be readily wholesaled in places like Florida where there is a high demand and an insufficient supply.

The distributor would pick up the LCO₂ in twenty-ton quantities from a storage tank at the manufacturer's facility. Terms of sale would be FOB, the manufacturer's storage tank. Distributors would prefer to deal with a manufacturer that can supply several hundred tons per day, however, in markets with a low supply to demand ratio, a supplier of smaller daily quantities could find a ready buyer.

The purity of the LCO₂ must be certified and the supplier must be responsible for any contamination of the distributor's or end user's trucks, storage facilities or final product. Purity must be continually monitored by the manufacturer.

Much of the LCO₂ produced is used in the food industry. This poses a potential marketability problem for the manufacturer of LCO₂ from Landfill Gas (LFG). Some food processors may be afraid to be condemned for using carbon dioxide *from a garbage dump* to produce food. While the problem is more one of perception than of substance, it is no less real.

There are many industrial applications for LCO₂. If there is a sufficient demand from industrial applications in the market, the perception problems by the food industry may not be a matter for concern by the manufacturer of the carbon dioxide.

Appendix B contains a list of some of the commercial uses of CO₂.

C.7. Subtask 3.7. Determine which, if any, Models are Commercially Feasible

There are actually two models. The first is concerned with a practical model or set of circumstances which will make the Acrion LFG to LNG and LCO₂ separation and conversion plant commercially viable. The second model is concerned with the set of circumstances which will make the use of LNG as a transportation fuel commercially viable. The two models are related but are also sufficiently independent to warrant separate examination.

Acrion LFG to LNG and LCO₂ Technology

The following criteria should be met to make the installation of an Acrion LFG to LNG and LCO₂ separation and conversion facility commercially viable.

Source of LFG: The larger the supply of LFG, the more economically feasible it is to make the necessary capital investment and operate the facility. The largest plant model presented in this report is 5.0 million Standard Cubic Feet per Day (SCFD). A larger plant with a commensurate source of LFG would improve the economies of scale for both construction and operation even further. The limiting factors will be the ability of the marketplace in the geographic area to consume the LNG and LCO₂ produced.

The rate of LFG produced each day and the chemical composition must be considered. The rate of LFG gas flow must meet the minimum requirements to supply the separation and conversion plant's daily consumption. This projected production of LFG must occur for a sufficient number of years to meet the debt service requirements of the capital investment and any contracts for the sale of the LNG and LCO₂.

The expected chemical composition of the gas must be predictable so that the plant can run smoothly without major adjustments in operation or the need to reengineer the plant. Radical and unpredictable changes in the chemical composition of the gas could cause significantly increased operating and/or construction costs.

Market for the LNG and LCO₂: In order for the construction of the LFG separation and conversion plant on the landfill to be a practical investment, there must be markets for both the methane and the carbon dioxide at prices above the breakeven level to recover the construction investment and cover the cost of production. The three plant models presented in this report are based on the need to produce LNG and LCO₂, however, there are other combinations of products that could be produced including methane as a gas, methanol, and carbon dioxide as a gas.

In the LCO₂ scenario, the LFG separation and conversion plant will have to be located in a part of the country where there is a market for the product. As mentioned in Subtask 6, certain parts of the country already have an over supply of carbon dioxide and a relatively small demand. In addition, it would be best if the demand for carbon dioxide is for uses other than for carbonated beverages or food processing.

Ownership: Because of the very thin margins projected by the three models in this report, for the production net positive cash flow from operation, the cost of funds must be low

and the length of time for payback must be relatively long. Cost of funds is not necessarily the cost to borrow money, but rather includes the lost opportunity cost of the investment.

It may not be necessary to borrow the money to make the investment, however, for the investment to make sense, it must provide a better expected return on investment than all other available investment options. Three factors which must be considered when determining whether to make an investment are:

1. what is the cost of the money to be invested? - the return must be greater than the cost.
2. what is the risk of the investment? - the expected return on the investment must be sufficient to cover the cost of the money to be invested and also cover the perceived risk associated with the investment.
3. what is the expected return and perceived risk of all alternative available investment opportunities? - rational investing requires investing available funds first in those opportunities which provide the best mix of high expected return on the investment and low perceived risk.

Any time a new technology is being put into commercial use, there is a relatively high risk. What has been proven to work on a pilot or trial basis may not perform as well on a full commercial scale.

The cost of funds required by a commercial venture will almost always be greater than what a governmental entity would incur. In addition, a governmental agency could normally secure financing for a longer period of time than a commercial venture. A third factor is that governmental organizations do not normally have to pay tax on revenue received. Finally, commercial enterprises must make investments that anticipate generating a profit, governmental agencies need only be assured of generating sufficient cash to cover expenses as they arise. Given these factors, it is easier for the government owned facility to generate the revenue necessary to meet expenses and service debt than a commercial enterprise.

Therefore, the initial installations of the LFG separation and conversion plants should probably be owned by government agencies; however, for efficiency, these should probably operate under contract by a commercial venture.

There is a possibility that some low cost, tax free financing could be secured in special circumstances for private investment.

Summary: In order for the LFG separation and conversion plant to be successful, it should:

- Be engineered to process at least than 5.0 million SCFD of LFG
- Be located in a geographical area that has markets that can absorb the full production of both methane and carbon dioxide
- Be owned (the first few) by government agencies and probably operated under contract by a commercial enterprise

Use of LNG as a Transportation Fuel

To be economically feasible, LNG must be commercially attractive to use as an alternative to other fuels; it cannot be attractive only if there are large governmental subsidies or onerous restrictive mandates. To be a success, LNG as a transportation fuel must, in economic terms, pass the test of *allocative efficiency*³⁴ and *productive efficiency*.³⁵

The following criteria must be met collectively to make the use of LNG as a transportation fuel practical:

1. The cost of the fuel must be competitive with all alternative fuels including Diesel.
2. The cost of operating and maintaining the vehicles must be competitive with vehicles operated on other fuels, including Diesel.
3. The initial cost of vehicles operated on LNG must be competitive with vehicles operating on other fuels including Diesel.
4. LNG must be readily available within the operating territory of the vehicle.

Fuel Cost: At today's cost of Diesel fuel, the LNG must be able to be delivered to the refueling point for between \$0.40 and \$0.45 per gallon before taxes are added. This makes the cost equal to a gallon of Diesel, at between \$0.672 and \$0.765 before taxes are added. The cost of delivery is about \$0.03 and \$0.04 per gallon of LNG per 100 miles transported.³⁶

Operation and Maintenance Costs³⁷: Research by the Clean Air Partnership in San Diego, California, indicates that the operating and maintenance costs of Diesel engines converted to operate on a dual fuel combination of Diesel and LNG require the replacement of parts that normally wear out in use, at only 25% to 50% of the rate of an all Diesel engine. Such preventative maintenance as changing oil may never have to be done.

The expected service life of the dual fuel Diesel/LNG engines is two to four times that of a conventional Diesel engine. However, this expected extended service life is not a material factor in the investment decision. Since the typical service life of a heavy duty Diesel engine could be 700,000 miles, the fact that it will operate for two to four times that becomes irrelevant. The important consideration is that the expected service life is no less than for a conventional Diesel engine.

Under certain laboratory conditions, the thermal efficiency of the Diesel/LNG dual fuel engine is equal to that of a conventional Diesel engine.

Therefore, the technology already exists to provide an engine which uses LNG as the primary fuel with has operating and maintenance properties competitive with a conventional Diesel engine.

Capital Costs³⁸: The cost of a dual fuel Diesel/LNG engine are, today, about 40% higher (including the cryogenic fuel tanks on the vehicle) than a conventional Diesel engine. However, the cost differential was reduced by about 50% in the past year and is expected to continue to fall for the foreseeable future. If and when the dual fuel engine becomes an

off-the-shelf, assembly line item, the cost differential should become minimal. The cost of the fuel tanks, however, will probably always be greater than a standard Diesel fuel tank because of the necessities of holding a cryogenic fluid.

Therefore, the cost of purchasing a vehicle with a dual fuel, Diesel/LNG engine has come down and should continue to come down.

Availability of LNG as a Fuel: LNG must be available for the vehicle to refuel before the fuel is entirely consumed. At the moment, there is not a national or even regional network of LNG fueling stations. Therefore, until such a time as there is some kind of a network of LNG refueling points, each fleet operator must provide for an internal refueling plan. In most cases, the fleet operations will be limited to a range where the vehicles can return to a central point each time refueling is required. In some cases, the fleet operator may provide refueling points along, or at the terminal points, of a route or network of routes.

The lack of a network of LNG refueling points is currently the most significant limiting factor to the successful widespread adoption of LNG as a primary transportation fuel.

Summary: The cost of maintenance on LNG dual fuel engines should be less than for a conventional Diesel, and the difference in initial investment should only be marginally different, as more of the dual fuel engines are produced. The only remaining hurdles are the cost and availability of LNG. An LFG separation and conversion plant using the Acrion technology could be cost effective to produce LNG from LFG as long as the fuel does not have to be transported more than two to three hundred miles. The market price of LNG is also at a point where it can be purchased and transported one or two hundred miles and still be on a parity with Diesel fuel. A problem is that many parts of the United States are not within a few hundred miles of a major LNG production point.

The last and seemingly most difficult obstacle is the lack of a network of LNG refueling stations; this lack limits the range of a vehicle to no further than a return trip to a single central refueling point.

C.8. Subtask 3.8. Identify Possible Future Risk and Opportunity Scenarios

The commercial feasibility of both the LFG separation and conversion plant and the use of LNG as a transportation vehicle fuel are based on a number of economical and political assumptions. If the circumstances of any of those assumptions change there could be either a positive or negative impact on the relative advantages and disadvantages of both LNG as a transportation fuel and the use of the Acrion technology to separate and convert LFG to LNG and LCO₂. Some of the risk scenarios include:

- Today the U.S. dollar is used to price crude oil. As the Euro comes into use, it is possible that for both economics as well as political reasons, OPEC could change policy and price crude oil in Euros rather than dollars. If OPEC switched to pricing crude in the Euro and the value of the Euro went up against the dollar, all products (including Diesel fuel) that use crude as a basic hydrocarbon feedstock would become more expensive to produce. The pressures of demand for substitute goods (LNG) would tend to increase LNG prices as well; however, the immediate price increases would not be as great as for crude, thus giving LNG a relative price advantage for a period of time.
- On the other hand, if OPEC chose to switch the pricing of crude to the Euro and the Euro declined against the dollar (a possible scenario should political infighting breakout among the members of the European Union) the products that use crude oil as a feedstock would decline in price significantly reducing the commercial advantage of using LNG as a transportation fuel.
- If major new oil reserves were discovered and put into production or if new technology significantly reduced the cost of unlocking crude from shale or sand, the increased supply of crude would reduce the equilibrium price and reduce the comparative advantage of LNG.
- Political instability in the Middle East or another OPEC embargo would again display the advantages of a stable source of transportation fuel to large fleet owners and railroads. This would work to LNG's advantage.
- The successful development of other alternative fuels could reduce the market for LNG. In January 1999, the first liquid hydrogen filling station was opened in Germany.

C.9. Subtask 3.9 Public Policy Considerations

Public Policy Criteria

If there is value to our society to convert Landfill Gas (LFG) to useable products and to encourage the conversion of vehicles to Liquid Natural Gas (LNG) as a primary fuel, what criteria should be used to formulate public policy issues?

The value to our society to convert LFG to useable products

As human beings, we have an insatiable appetite for goods and services yet we are faced with a planet that provides limited resources. The more we can use technology to make resources available, the more of the goods and services that we desire can be produced and the more our standard of living can potentially be improved. This is referred to as being able to shift our *production possibilities curve to the right*. Clearly the ability to harness LFG to produce methane and carbon dioxide increases our available supply of raw materials, shifts our *production possibilities curve* to the right and ultimately has the potential to increase our standard of living.

A key consideration, however, is that when we have completed the process of producing methane and carbon dioxide - and delivering it to where it will be used, we can not have used more net resources in the production and transportation than we produced and delivered. Additionally, the resources that we used to produce and deliver the methane and the carbon dioxide must have been the best possible use for those resources. These economic principles are known as *allocative efficiency*³⁴ and *productive efficiency*³⁵.

Next, there may be some value to our environment to be able to utilize LFG to produce methane and carbon dioxide. Methane and carbon dioxide are going to be produced naturally by the decomposition of the refuse in a landfill. If these naturally occurring chemicals are harnessed and used to fill existing demand, other methane and carbon dioxide will not have to be produced and ultimately released into the atmosphere.

The value to our society to use LNG as a primary transportation fuel

The benefits to our society involve economic and political independence from OPEC. Additionally, there is the benefit of a more stable and predictable cost of fuel.

The United States and Canada have the ability to produce large amounts of natural gas. Any demand for crude oil that can be satisfied with natural gas reduces the amount of crude oil that needs to be imported. Therefore, a larger percentage of our crude oil consumption can be satisfied by crude produced in this country and other non-OPEC nations. This reduction of our dependence on the OPEC nations gives this country more potential flexibility in the conduct of foreign affairs.

For the owners and operators of fleets of vehicles and transportation systems dependent on Diesel fuel, a switch to LNG provides a more stable and predictable energy cost. A change to a fuel produced in the United States, also frees them from the negative impact of another crude oil embargo.

What criteria should be used to formulate public policy issues?

It would be best if the natural forces of our market economy dictated the resources that our society used, in what amounts, and for what purposes. However, there are one or two hurdles that our market economy may not cross for many years to come. Therefore, if there is going to be any adjustments to the mechanisms of our market economy, on what basis should this be done?

Some suggested criteria for possible adjustment of the market economy include:

- Any meddling with market forces should be temporary. Both technology and the marketplace can have fundamental and radical changes within short time frames. What seems to be appropriate today may be harmful in a small amount of time.
- Public policy should "prime the pump" then let the natural market forces of supply and demand lead the way and sustain any change in the allocation and use of our resources.
- The natural *allocative* and *productive efficiencies* provided by the marketplace should be left alone as much as possible. Any taxes, government subsidies, licensing requirements, mandated use of one thing, or the restriction of use of something else will interfere with market dictated best uses of resources, reduce the production possibilities of our economy, and potentially reduce our standard of living - all other things being equal.
- The least amount of burden should be placed on those who benefit least.

Public Policy Considerations

In as much as it has been determined that there are both economic and political benefits to some change from Diesel to LNG as a transportation fuel and to using Landfill Gas (LFG) to produce methane and carbon dioxide, temporary public policy to encourage these changes seems justified and can be considered.

Consideration of the issues of separation and conversion of LFG and the issue of transition from Diesel to LNG as a primary fuel for some vehicles will be treated separately.

Landfill Gas Separation and Conversion

The fact that the Acirion technology which separates and converts LFG to methane and carbon dioxide for commercial use has not been demonstrated on a full commercial scale is a challenge to overcome. If a full scale demonstration is successful, the potential net positive cash flow that it can generate will create its own demand and natural market forces will takeover. Therefore, the following public policy is recommended:

- The appropriate Federal Agency underwrite the installation of three to five LFG separation and conversion plants by local or state governments. The underwriting would provide for the Federal government agency to guarantee that the state or local government which made the investment would generate sufficient revenue from the sale of the methane and carbon dioxide to cover operating expenses and service the debt incurred in building the facility.

- The appropriate Federal agency would purchase the methane and carbon dioxide produced at fair market value, only if other buyers could not be found.

Benefits:

- Successful demonstration of the technology in a full scale facility will create a demand for use in the private sector.
- Successful demonstration of the technology in a full scale facility will reduce the risk of investment associated with a new technology. With reduced risk, the cost of funding the investment in the private sector can be reduced. Therefore, a private commercial investment can more easily cover operating expenses, earn a *normal profit*³⁹, and pay taxes.
- As more facilities are built, the marginal cost of each additional facility should come down.
- The state or local government has the potential to generate extra revenue to fund other projects if the facility operates as planned.
- New jobs could be created.
- The risk of failure will be spread across all of society, not just the taxpayers of the state or municipality which installs the facility. This is appropriate because all of society could benefit from a successful outcome.
- The state or local government can probably reduce the cost of borrowing to build the facility because there is the full faith and credit of the Federal Government standing behind the project.
- The potential costs to the Federal government agency are known and limited.

Costs:

- Cost to the U.S. taxpayer is limited to the debt service of the funding.
- If the initial demonstration project is unable to sell the gases and the U.S. taxpayer is forced to purchase the methane or carbon dioxide produced at fair market prices, the value of the two chemicals compensates the government, at least in part, for the cost of the purchases. (It is assumed that the Federal government has use for both chemicals.)
- If the cost of operating the plant is greater than the value of the methane and the carbon dioxide produced, the plant should be closed and the cost to the U.S. taxpayer is still limited to the cost to service the debt.

Use of LNG as a Primary Fuel for Transportation:

There remains only one major hurdle and some minor obstructions. The final remaining hurdle that will not be easily or quickly be resolved by natural marketplace forces is the lack of a network of LNG fueling stations. Some of the minor obstacles include the prohibition of the use of LNG as a transportation fuel in some parts of the country. If the problem of the availability of LNG on a national or even regional basis can be overcome, market forces will be free to encourage the transition of at least some vehicles to use LNG as a primary fuel. As long as LNG is available, market forces will encourage the conversion of railroad locomotives and commercial water transportation to convert. Municipal busses are somewhat insulated from the problems of a lack of a network of refueling locations because most will return to a central location for refueling. Therefore, any public policy should focus on the use of LNG as a primary fuel for class 7 and 8 trucks. Again this public policy should meet the economic criteria previously outlined.

If the demand for engines operated on LNG increases, the economies of scale for manufacturing and the competition among the engine producers will drive the cost of the engines down to the point where there will be little marginal difference with Diesel engines. The reduction in maintenance costs and costs of unscheduled downtime should compensate for remaining marginal cost differences.

The recommended public policy is:

- Designate one or more sections of interstate highways which are highly traveled by class 7 and 8 long haul trucks - routes that would get the most potential benefit from conversion to LNG. These routes must be near sources of LNG or near large landfills that have or could have LNG separation and conversion plants constructed and operating so that the cost of transporting the fuel does not make the cost of the fuel at the pump greater than the *Diesel Equivalent* cost of fuel. (1.68 gallons of LNG equal 1 gallon of Diesel)
- Along these routes, contract with existing well operated and financially strong truck stops at reasonable intervals and near major metropolitan areas to install LNG refueling points.
- Provide in the contract that the truck stop owner/operator will share in any revenue generated by the sale of LNG. However, the amount of revenue received by truck stop would be less than if the truck stop owned the equipment.
- As long as the Federal government owned the LNG refueling equipment, there would be no property tax on the specified equipment. Income tax would be paid by the truck stop on any profits generated.
- Agree to keep the LNG refueling stations in operation for a minimum period of time such as 10 to 20 years in order to assure any truck operator that there would be a supply of LNG for a sufficient length of time to make investment in and LNG powered vehicle practical.

- Give the truck stop owner the option to purchase the LNG refueling equipment at fair market value, at any time, with the provision that the refueling operation must remain in operation for the period of time originally committed to by the Federal government.

Benefits:

- Fleet owners that operate within the designated route will know that they will have an assured source of fuel for the service life of the vehicles.
- Owners of vehicles that operate within the metropolitan areas along the designated route will be able to refuel relatively conveniently.
- The conversion of some vehicles to LNG will encourage the major engine manufacturers to produce the engines on a more economical and efficient scale, compete (which will reduce marginal cost differentials with conventional Diesel engines), and encourage more investment in research and development for even more efficient engine operation and manufacturing.
- The cost of LNG refueling equipment should be driven down by economies of scale and competition.
- The successful conversion of a "critical mass" of vehicles in an area and the demonstration of the profitability of operating an LNG refueling station will encourage the owners of other truck stops both on and adjacent to the designated routes to invest in LNG refueling equipment.
- Once the critical mass has been attained and the use of LNG as a primary transportation fuel has been successfully demonstrated, market demand will tie the designated routes together into a national network.
- As the demand for LNG spreads across the nation, suppliers of natural gas will be encouraged by market demand to provide facilities to produce high quality LNG thus bringing the supply closer to the point of use and reducing the cost of transporting the fuel⁴⁰.

Costs:

- The costs to the U.S. taxpayer are those of installing the equipment and administering the contracts for the LNG refueling points on the designated routes.
- The costs will be reduced by sharing the revenue generated by the refueling stations, and when truck stop owners purchase the equipment from the Federal government.

End Notes

¹ Class 6 vehicles have a Gross Vehicle Weight (GVW) under 26,000 pounds, class 7 vehicles have a GVW between 26,000 and 32,999 pounds, and class 8 vehicles have a GVW between 33,000 and 79,999 pounds.

² *Weathering* is the process whereby different chemicals evaporate at different rates which causes the chemical composition of the remaining material to change over time.

³ In 1991, the U.S. EPA designated municipal solid waste landfill emissions as a pollutant because the volatile organic compounds in LFG interact with nitrous oxides to form ozone... At that time the EPA proposed regulations requiring the gases to be collected. The EPA estimated that 500 to 700 landfills would be affected by the regulations (See DOE document DE953000208)

⁴ The LFG Input Requirement is the minimum amount of LFG required each day to be fed to the recovery facility. The LFG is assumed to contain 50% CH₄, 49% CO₂, and 1% Nitrogen.

⁵ The Operating Parameters relate to the efficiency of recovery. In the case of Methane, the RLM (Refrigerated Liquid Methane) will be equal to 73% of the Methane contained in the LFG prior to processing.

⁶ For the purposes of this model, the processing facility is expect to operate 24 hours per day, 350 days per year.

⁷ The assumption is made that electricity will cost \$0.05 per kWh.

⁸ There is no expense estimated for the purchase of LFG from the landfill operator. The landfill operator could be paid on the basis of the LFG consumed, a flat rate per year, on a "take or pay" basis for estimated minimum consumption rates, or share in the profits or gross revenues. It is also possible that the landfill operator might pay to have the LFG taken by the operator of the LFG processing facility.

⁹ There is no expense estimated for the purchase of LFG from the landfill operator. The landfill operator could be paid on the basis of the LFG consumed, a flat rate per year, on a "take or pay" basis for estimated minimum consumption rates, or share in the profits or gross revenues. It is also possible that the landfill operator might pay to have the LFG taken by the operator of the LFG processing facility.

¹⁰ The LFG Input Requirement is the minimum amount of LFG required each day to be fed to the recovery facility. The LFG is assumed to contain 50% CH₄, 49% CO₂, and 1% Nitrogen.

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²² Dr. John Beck, Clean Air Partnership, San Diego, California in a phone interview on January 7, 1999.

²³ Desirability LNG with a near 100% pure methane content were mentioned in interviews with both John Bartel, Mack Truck and Dr. John Barclay, University of Victoria, British Columbia, Canada

²⁴ Interview with Jerry Simmons, Shop supervisor, William H. Martin Landfill, Washington Pennsylvania on December 3, 1998

²⁵ Interview with Jerry Simmons, Shop supervisor, William H. Martin Landfill, Washington Pennsylvania on December 3, 1998

²⁶ Information provided by Jeff Beale, President of CH-IV, Inc. in a telephone interview on January 7, 1999

²⁷ Please see the article in Appendix B: *Design and Operation of 'Self-Serve' LNG Fueling Stations* by Jeff Beale. CH-IV Cryogenics, November 3, 1997 and *Description of the CH-IV LNG Dispenser* also written by Jeff Beale, November 4, 1997.

²⁸ A Diesel equivalent gallon is the amount of LNG required to equal the BTU energy content of one gallon of Diesel fuel. It takes approximately 1.7 gallons of LNG to equal the BTU content of one gallon of Diesel fuel.

²⁹ Information provided by Dr. John Barclay, Professor at the University of Victoria, British Columbia, Canada in a phone interview on January 7, 1999

³⁰ Class 7 trucks have a Gross Vehicle Weight (GVW) between 26,000 pounds and 32,999 pounds. Class 8 trucks have a GVW between 33,000 pounds and 79,999 pounds .

³¹ Notes from the GasRail Industry Wide Meeting, Lowes L'engant Plaza Hotel, Washington, D.C., March 1, 1994

³² *Alternative Railroad Fuels*, a presentation by Dr. James Ortner, Manager, Air Quality Program, Orange County Transportation Authority / Southern California Regional Rail Authority, at the GasRail USA Industry-Wide Meeting, Lowes L'enfant Plaza Hotel, Washington, D.C., March 1, 1994

³³ Wholesale market price information provided by David Forstrom, Praxair, Chicago, Ill.

³⁴ "The apportionment of resources among firms and industries to obtain the production of the products most wanted by society; the output of each product at which its marginal cost and price or marginal benefit are equal." *Economics - Principles, Problems, and Policies*, 14th Edition, McConnel and Brue, McGraw-Hill, 1999.

³⁵ The production of a good in the least costly way; occurs when production takes place at the output at which average total cost is a minimum and at which marginal product per dollar's worth of input is the same for all inputs. *Economics - Principles, Problems, and Policies*, 14th Edition, McConnel and Brue, McGraw-Hill, 1999.

³⁶ Dr. John Beck in a phone interview on January 7, 1999.

³⁷ Dr. John Beck in a phone interview on January 7, 1999

³⁸ Dr. John Beck in a phone interview on January 7, 1999

³⁹ *Normal Profit* is defined as: "The payment made by a firm to obtain and retain entrepreneurial ability; the minimum income which entrepreneurial ability must receive to induce it to perform entrepreneurial functions in a firm." *Economics - Principles, Problems, and Policies*, 14th Edition, McConnel and Brue, McGraw-Hill, 1999.

⁴⁰ Please see the article *LNG for peak delivery possible in the US in near future* in Appendix B.

APPENDIX A

Detailed Flowsheets, Material Balances, and Equipment Sizing

Figure A-1, Contaminant and CO₂ Removal

Figure A-2, Compression and Dehydration

Figure A-3, Contaminant and Bulk CO₂ Removal

Figure A-4, Feed Cooler and CO₂ Condenser

Figure A-5, Residual CO₂ Removal

Table A-1, Material Balance for Figure A-1

Table A-2, Material Balance for Figure A-4

Figure A-6, Methane Liquefaction

Table A-3, Material Balance for Figure A-6

Figure A-7, Ethylene Refrigeration

Table A-4, Material Balance for Figure A-7

Figure A-8, Propane Refrigeration

Table A-5, Material Balance for Figure A-8

Table A-6, Equipment Size

FIGURE A-1
CO2 AND CONTAMINANT REMOVAL

FIGURE A-4
RESIDUAL CO₂ REMOVAL

FIGURE A-5

Feed Cooler and CO2 Condenser

Table A-1, Material Balance for Figure A-1

Stream	99	100	102	103	104	105
Vapour frac.	1	1	1	0.9968	1	1
Temperature F	70.00	72.45	319.48	100.00	100.00	351.91
Pressure psia	14.7	14.7	60	55	55	220
Methane lbmole/hr	239.32	286.29	286.29	286.29	286.29	286.29
Nitrogen lbmole/hr	4.31	5.28	5.28	5.28	5.28	5.28
CO2 lbmole/hr	234.54	282.40	282.40	282.40	282.40	282.40
H2O lbmole/hr	12.59	12.59	12.59	12.59	10.72	10.72
Contam. lbmole/hr	0.11	0.11	0.11	0.11	0.11	0.11
Total: lbmole/hr	490.87	586.67	586.67	586.67	584.80	584.80
Stream	106	107	108	109	110	111
Vapour frac.	0.9869	1	1	1	1	1
Temperature F	100.00	100.00	100.00	95.73	317.22	100.00
Pressure psia	215	215	210	210	715	715
Methane lbmole/hr	286.29	286.29	286.29	339.24	339.24	339.24
Nitrogen lbmole/hr	5.28	5.28	5.28	5.78	5.78	5.78
CO2 lbmole/hr	282.40	282.40	282.40	454.46	454.46	454.46
H2O lbmole/hr	10.72	3.05	0.00	0.00	0.00	0.00
Contam. lbmole/hr	0.11	0.11	0.11	0.12	0.12	0.12
Total: lbmole/hr	584.80	577.13	574.08	799.60	799.60	799.60
Stream	112	113	114	114a	115	116
Vapour frac.	1	0	0.6763	0.2999	0.1108	0.9982
Temperature F	6.38	5.19	-31.58	-43.58	-60.00	-40.00
Pressure psia	715	715	210	210	101.03	96.03
Methane lbmole/hr	339.24	21.02	21.02	21.02	0.66	0.66
Nitrogen lbmole/hr	5.78	0.20	0.20	0.20	0.00	0.00
CO2 lbmole/hr	454.46	162.46	162.46	162.46	58.72	58.72
H2O lbmole/hr	0.00	0.00	0.00	0.00	0.00	0.00
Contam. lbmole/hr	0.12	0.11	0.11	0.11	0.11	0.11
Total: lbmole/hr	799.60	183.79	183.79	183.79	59.49	59.49
Stream	117	118	119	120	121	122
Vapour frac.	0.9985	1	0	1	0.2647	0
Temperature F	-47.00	85.00	-31.58	-31.58	-38.98	0.28
Pressure psia	65.04	60.04	210	210	250	701.76
Methane lbmole/hr	0.66	0.66	0.66	20.36	32.59	32.59
Nitrogen lbmole/hr	0.00	0.00	0.00	0.20	0.30	0.30
CO2 lbmole/hr	58.72	58.72	58.72	103.73	239.19	239.19
H2O lbmole/hr	0.00	0.00	0.00	0.00	0.00	0.00
Contam. lbmole/hr	0.11	0.11	0.11	0.01	0.00	0.00
Total: lbmole/hr	59.49	59.49	59.49	124.30	272.08	272.08

Table A-1, Material Balance for Figure A-1, Continued

Stream	123	124	124a	125	126	126r
Vapour frac.	1	1	1	0	1	1
Temperature F	-35.06	-75.01	-38.82	-11.76	-36.25	-36.25
Pressure psia	250	700	695.00	250	210	210
Methane lbmole/hr	32.59	285.63	285.63	0.00	52.95	52.95
Nitrogen lbmole/hr	0.30	5.28	5.28	0.00	0.50	0.50
CO2 lbmole/hr	68.32	52.82	52.82	170.87	172.05	172.06
H2O lbmole/hr	0.00	0.00	0.00	0.00	0.00	0.00
Contam. lbmole/hr	0.00	0.00	0.00	0.00	0.01	0.01
Total: lbmole/hr	101.21	343.72	343.72	170.87	225.51	225.52
Stream	127	200	201	202	202r	203
Vapour frac.	1	1	1	1	1	1
Temperature F	85.00	20.00	0.47	0.47	0.47	9.39
Pressure psia	210	695.00	690	20	20	685
Methane lbmole/hr	52.95	285.63	238.66	46.96	46.96	238.66
Nitrogen lbmole/hr	0.50	5.28	4.30	0.98	0.98	4.30
CO2 lbmole/hr	172.06	52.82	4.96	47.86	47.86	0.01
H2O lbmole/hr	0.00	0.00	0.00	0.00	0.00	0.00
Contam. lbmole/hr	0.01	0.00	0.00	0.00	0.00	0.00
Total: lbmole/hr	225.52	343.72	247.92	95.80	95.80	242.98
Stream	204	209	216	218	300	305b
Vapour frac.	0	1	1	1	1	1
Temperature F	9.73	-10.00	85.00	-50.77	-70.00	-80.00
Pressure psia	690	20	15	210	680	20
Methane lbmole/hr	0.00	41.22	46.96	11.13	238.66	41.22
Nitrogen lbmole/hr	0.00	3.84	0.98	0.04	4.30	3.84
CO2 lbmole/hr	4.95	0.00	47.86	2.37	0.01	0.00
H2O lbmole/hr	0.00	0.00	0.00	0.00	0.00	0.00
Contam. lbmole/hr	0.00	0.00	0.00	0.00	0.00	0.00
Total: lbmole/hr	4.95	45.06	95.80	13.54	242.98	45.06
Stream	Water1	Water2	Water3			
Vapour frac.	0	0	---			
Temperature F	100	100	---			
Pressure psia	55	215	---			
Methane lbmole/hr	0.00	0.00	0.00			
Nitrogen lbmole/hr	0.00	0.00	0.00			
CO2 lbmole/hr	0.00	0.00	0.00			
H2O lbmole/hr	1.87	7.67	3.05			
Contam. lbmole/hr	0.00	0.00	0.00			
Total: lbmole/hr	1.87	7.67	3.05			

Table A-1, Material Balance for Figure A-1, Continued

Compressors						
Stream		WK101	WK102	WK103		
Enthalpy Hp		532.7	543.6	618.0		
Heat Exchange						
Stream		qcond	qreb	qac101	QAC102	QAC103
Enthalpy Btu/hr		2,114,520	259,646	1,264,870	1,596,420	1,897,860
Stream		Qhx104	Qhx105	QHX106	Qhx107	Qhx201
Enthalpy Btu/hr		955,818	270,519	363,564	74,379	233,070
Stream		Qhx202	QHX108	qhx200a	qhx200b	qhx200ab
Enthalpy Btu/hr		71,282	447,576	189,529	25,412	214,941

Table A-2, Material Balance for Figure A-4

Stream	111	111a	111b	111c	112	112a
Vapour frac.	1	1	1	1	1	1
Temperature F	100.00	100.00	100.00	47.16	6.38	6.38
Pressure psia	715	715	715	715	715	715
Enthalpy Btu/hr	3077780	1341440	1736340	1456790	2121960	924811
Methane lbmole/hr	339.24	147.85	191.38	191.38	339.24	147.85
Nitrogen lbmole/hr	5.78	2.52	3.26	3.26	5.78	2.52
CO2 lbmole/hr	454.46	198.07	256.39	256.39	454.46	198.07
H2O lbmole/hr	0.00	0.00	0.00	0.00	0.00	0.00
Contam lbmole/hr	0.12	0.05	0.07	0.07	0.12	0.05
Total: lbmole/hr	799.60	348.50	451.10	451.10	799.60	348.50
Stream	112b	114	114A	115	116	117
Vapour frac.	1	0.6763	0.2999	0.1108	0.9981	0.9984
Temperature F	6.39	-31.58	-43.58	-60.00	-41.68	-47.00
Pressure psia	715	210	210	101.03	96.03	72.72
Enthalpy Btu/hr	1197150	177863	-269702	-185689	176876	176876
Methane lbmole/hr	191.38	21.02	21.02	0.66	0.66	0.66
Nitrogen lbmole/hr	3.26	0.20	0.20	0.00	0.00	0.00
CO2 lbmole/hr	256.39	162.46	162.46	58.72	58.72	58.72
H2O lbmole/hr	0.00	0.00	0.00	0.00	0.00	0.00
Contam lbmole/hr	0.07	0.11	0.11	0.11	0.11	0.11
Total: lbmole/hr	451.10	183.79	183.79	59.49	59.49	59.49
Stream	118	126r	127	128	128a	129
Vapour frac.	1	1	1	1	0.9149	0.7988
Temperature F	85.00	-36.25	85.00	-15.60	-21.58	-31.68
Pressure psia	67.72	210	210	700.88	700.88	700.88
Enthalpy Btu/hr	251704	656803	927322	1966720	1654060	120649
Methane lbmole/hr	0.66	52.95	52.95	431.58	431.58	431.58
Nitrogen lbmole/hr	0.00	0.50	0.50	6.51	6.51	6.51
CO2 lbmole/hr	58.72	172.06	172.06	331.88	331.88	331.88
H2O lbmole/hr	0.00	0.00	0.00	0.00	0.00	0.00
Contam lbmole/hr	0.11	0.01	0.01	0.00	0.00	0.00
Total: lbmole/hr	59.49	225.52	225.52	769.98	769.98	769.98
Stream	130	131	202r	206	209	216
Vapour frac.	0.7095	0.4465	1	1	1	1
Temperature F	-41.47	-75.00	0.47	-64.96	-81.50	85.00
Pressure psia	700	700	20	20	18	15
Enthalpy Btu/hr	843930	-147623	343004	92262	184338	414287
Methane lbmole/hr	431.58	431.58	46.96	4.79	40.81	46.96
Nitrogen lbmole/hr	6.51	6.51	0.98	0.00	4.13	0.98
CO2 lbmole/hr	331.88	331.88	47.86	26.32	18.42	47.86
H2O lbmole/hr	0.00	0.00	0.00	0.00	0.00	0.00
Contam lbmole/hr	0.00	0.00	0.00	0.00	0.00	0.00
Total: lbmole/hr	769.98	769.98	95.80	31.11	63.36	95.80

Table A-2, Material Balance for Figure A-4, Continued

Stream		qreb	qhx104a	QFeedCool	QHX105
Enthalpy	Btu/hr	259,646	416,630	279,550	270,519
Stream		QHX107	QCO2Cond	QCO2Cond2	QHX202
Enthalpy	Btu/hr	74,828	991,553	312,660	71,282

FIGURE A-6
METHANE LIQUEFACTION

Table A-3, Material Balance for Figure A-6

Stream	300	302	303	304	305	305a
Vapour frac.	1	1	0	0	1	1
Temperature F	-70.00	-73.68	-124.70	-176.13	-134.70	-139.25
Pressure psia	680	680	670	660	58	25
Methane lbmole/hr	238.66	423.85	423.85	423.85	41.22	41.22
Nitrogen lbmole/hr	4.30	11.20	11.20	11.20	3.84	3.84
CO2 lbmole/hr	0.01	0.02	0.02	0.02	0.00	0.00
Total: lbmole/hr	242.98	435.06	435.06	435.06	45.06	45.06
Stream	305b	306	306a	307	308	308a
Vapour frac.	1	0	0.2316	0	0	0.1182
Temperature F	-80.00	-176.13	-223.46	-176.13	-223.46	-253.03
Pressure psia	20	660	63	660	63	20
Methane lbmole/hr	41.22	284.59	284.59	139.25	222.70	222.70
Nitrogen lbmole/hr	3.84	7.52	7.52	3.68	1.75	1.75
CO2 lbmole/hr	0.00	0.01	0.01	0.01	0.01	0.01
Total: lbmole/hr	45.06	292.12	292.12	142.94	224.46	224.46
Stream	309	310	311	312	313	314
Vapour frac.	0	0.0434	1	1	1	1
Temperature F	-253.03	-183.85	-134.70	70.00	-223.46	-134.70
Pressure psia	20	200	195	190	63	58
Methane lbmole/hr	197.45	139.25	139.25	139.25	61.89	61.89
Nitrogen lbmole/hr	0.46	3.68	3.68	3.68	5.77	5.77
CO2 lbmole/hr	0.01	0.01	0.01	0.01	0.00	0.00
Total: lbmole/hr	197.92	142.94	142.94	142.94	67.66	67.66
Stream	314a	315	316	317	318	319
Vapour frac.	1	1	1	1	1	1
Temperature F	-134.70	70.00	86.31	325.14	100.00	-78.25
Pressure psia	58	53	53	195	190	680
Methane lbmole/hr	20.68	20.68	45.93	45.93	45.93	185.19
Nitrogen lbmole/hr	1.93	1.93	3.21	3.21	3.21	6.89
CO2 lbmole/hr	0.00	0.00	0.00	0.00	0.00	0.01
Total: lbmole/hr	22.60	22.60	49.14	49.14	49.14	192.08

Table A-3, Material Balance for Figure A-6, Continued

Stream	319r	320	321	322	323	324
Vapour frac.	1	1	1	1	1	1
Temperature F	-78.25	-253.03	-134.70	70.00	300.32	100.00
Pressure psia	680	20	18	16	58	53
Methane lbmole/hr	185.18	25.26	25.26	25.26	25.26	25.26
Nitrogen lbmole/hr	6.90	1.28	1.28	1.28	1.28	1.28
CO2 lbmole/hr	0.01	0.00	0.00	0.00	0.00	0.00
Total: lbmole/hr	192.08	26.54	26.54	26.54	26.54	26.54

Stream	325	326	327	328	LNG
Vapour frac.	1	1	1	1	0.0251
Temperature F	77.66	312.33	100.00	-69.77	-259.68
Pressure psia	190	690	685	680	14.7
Methane lbmole/hr	185.19	185.19	185.19	185.19	197.45
Nitrogen lbmole/hr	6.89	6.89	6.89	6.89	0.46
CO2 lbmole/hr	0.01	0.01	0.01	0.01	0.01
Total: lbmole/hr	192.08	192.08	192.08	192.08	197.92

Heat Exchange

Stream	QHX302	QHX303	QHX303A	QHX303B	QHX303C	QHX304
Enthalpy Btu/hr	815,021	511,091	50,091	25,226	435,767	339,883

Stream	QHX304A	QHX304B	QHX304C	QHX305	QHX306	Qhx307
Enthalpy Btu/hr	38,121	44,356	257,403	104,250	49,178	407,045

Compressors

Stream	WK301	WK302	Wk303
Enthalpy hp	21.8	42.0	157.0

FIGURE A-7
Ethylene Refrigeration System

Table A-4, Material Balance for Figure A-7

Stream	1	2	3	4	5	6
Vapour frac.	0	0.2061	1	0	0	1
Temperature F	-30	-80	-80	-80	-80	-80
Pressure psia	250.19	101.36	101.36	101.36	101.36	101.36
Molar Flow lbmole/hr	466.57	466.57	96.18	370.39	198.30	198.30
Ethylene mole frac.	1	1	1	1	1	1
Stream	7	8	9	10	11	12
Vapour frac.	0	0.1544	1	1	1	1
Temperature F	-80	-128	-128	-2.36	-51.24	65.48
Pressure psia	101.36	32.58	32.58	101.36	101.36	255.19
Molar Flow lbmole/hr	172.09	172.09	172.09	172.09	466.57	466.57
Ethylene mole frac.	1	1	1	1	1	1
Stream	13					
Vapour frac.	1					
Temperature F	22.84					
Pressure psia	255.19					
Molar Flow lbmole/hr	466.57					
Ethylene mole frac.	1					
Heat Exchange						
Stream	QCO2Cond	QHX302	QC2=Cond	qhx111		
Enthalpy Btu/hr	991,553	815,021	2,210,620	233,070		
Compressors						
Stream	WC2=CompH	WC2=CompL				
Enthalpy hp	71.79	178.61				

FIGURE A-8
Propane Refrigeration System

Table A-5, Material Balance for Figure A-8

Stream	21	22	23	24	25	26
Vapour frac.	0	0.2881	1	0	0	1
Temperature F	100	30	30	30	30	30
Pressure psia	190.26	66.68	66.68	66.68	66.68	66.68
Molar Flow lbmole/hr	619.18	619.18	178.40	440.78	38.78	38.78
Propane mole frac.	1	1	1	1	1	1
Stream	27	28	29	30	31	32
Vapour frac.	0	0.221	1	1	1	1
Temperature F	30	-40	-40.00	70.33	56.39	147.10
Pressure psia	66.68	16.06	16.06	66.68	66.68	190.26
Molar Flow lbmole/hr	402.00	402.00	402.00	402.00	619.18	619.18
Propane mole frac.	1	1	1	1	1	1

Heat Exchange

Stream	QFeedCool	QC2=Cond	QC3Cond
Enthalpy Btu/hr	279,550	2,532,280	4,294,160

Compressors

Stream	WC3CompL	WC3CompH
Enthalpy hp	258.75	323.83

Table A-6
Equipment Size
LNG +CO2 from 4.3 MMSCFD of LFG
Acron Contaminant Removal Process
and Membrane + Mol Sieve Final CO2 Removal

Tag	Service	Quantity	Size		Mat. + Press.
Compressors					
K101	Landfill Gas Stage 1	1	533	hp	
K102	Landfill Gas Stage 2	1	544	hp	
K103	Landfill Gas Stage 3	1	618	hp	
K301	Methane Stage 1	1	22	hp	
K302	Methane Stage 2	1	42	hp	
K303	Methane Stage 3	1	157	hp	
C2=CompL	Ethylene Stage 1	1	72	hp	
C2=CompH	Ethylene Stage 2	1	179	hp	
C3CompL	Propane Stage 1	1	259	hp	
C3CompH	Propane Stage 2	1	324	hp	
			2750	hp	
Exchangers					
HX104	Feed Cooler (105+107)	1	243	ft²	SS
HX202	Feed Cooler	1	452	ft²	CS
FeedCool	Feed Cooler -C3Ref	1	109	ft²	CS
strip Reboiler	Stripper Reboiler -Feed Cooler	1	110	ft²	CS
HX106	Contam. CO2 evap.-CO2 Cond	1	173	ft²	SS
CO2Cond	CO2 Condenser-C2=Ref	1	588	ft²	Al
HX200	Membrane Heat/Cool	1	250	ft²	Al
HX201	Membrane Heat	1	72	ft²	Al
HX108	CO2 Cond	1	460	ft²	SS
C2=Cond	CO2+C2=Cond-C3Ref	1	2054	ft²	Al
HX302	LNG Cond-C2=Ref	1	868	ft²	Al
HX303	LNG Subcooler	1	276	ft²	Al
HX304	LNG Recycle Gas Cooler	1	303	ft²	Al
HX308	LNG Recycle Gas Cooler	1	30	ft²	Al
C3Cond	C3 Condenser	1	10735	ft²	CS
Pumps					
abs100pump	Liquid CO2 Absorbent	2	1	hp	SS
Towers					
			Dia	Ht	
abs100	Contaminant Absorber	1	1.5	45'	CS 700 psi
strip	Methane Stripper	1	1'	30'	KCS 300 psi
Vessels					
			Dia	Ht	
abs100reflux	CO2 Reflux	1	2.5'	14'	SS 700 psi
sep	CO2 Flash	1	1.5'	8'	KCS 300 psi
PS302	LNG Flash 2	1	2.0'	9'	SS 200 psi
PS303	LNG Flash 3	1	2.0'	7'	SS 50 psia
Dehydration					
	Mol Sieve Beds+ Heater	2	3.0	14'	CS 300psi
CO2 Removal					
	Mol Sieve Beds+ Heater	2	6.0	15'	CS 700psi
H2S Removal					
	Sulfatreat Beds	2	5'	10'	CS 300psi
Storage					
	Liquid CO2 Storage Tank	1	62	KGal	CS 300psi
	LNG Tank	1	66	KGal	SS
Membrane					
	CO2 Removal Membrane	1			
Power					
	Electric Power	1	1136	kW	
	CS= Carbon Steel				
	SS= Stainless Steel				
	KCS = Killed Carbon Steel				

Appendix B

Attachments to Business Plan Section C

Task 3.1

Extraction of the Landfill Gas

Conversion and Separation Plant

1. Construction and Operating Cost analysis with support details for 2.0 million SCFD facility which purchases the electricity needed to operate it.
2. Construction and Operating Cost analysis with support details for 2.0 million SCFD facility which generates the electricity needed to operate it.
3. Construction and Operating Cost analysis with support details for 3.5 million SCFD facility which purchases the electricity needed to operate it.
4. Construction and Operating Cost analysis with support details for 3.5 million SCFD facility which generates the electricity needed to operate it.
5. Construction and Operating Cost analysis with support details for 5.0 million SCFD facility which purchases the electricity needed to operate it.
6. Construction and Operating Cost analysis with support details for 5.0 million SCFD facility which generates the electricity needed to operate it.

Task 3.3

Determine the Economics of Operating an LNG Filling Station

Beale, Jeff, *Description of the CH-IV LNG Dispenser*, CH-IV Cryogenics Internet Web Site, Article dated November 4, 1998

Beale, Jeff, *Design and Operation of 'Self-Serve' LNG Fueling Stations*, CH-IV Cryogenics Internet Web Site, Article dated November 3, 1997

Task 3.4

Determine the Commercial Feasibility of Purchasing, Converting, and Operating Vehicles on LNG

CALSTART, *Advanced Transportation Vehicle Catalog*, 1996

CALSTART, *Interstate Clean Transportation Corridor (ICTC), Market Barriers & Opportunities*, 1996

CALSTART, *Interstate Clean Transportation Corridor (ICTC), Regulatory barriers & Opportunities*, 1996

NREL list of locations that have the capability to refuel vehicles with LNG

Task 3.6

Determine the Economic Value of LCO₂

List of commercial uses for carbon dioxide

Table B 3.1-1
Capital, Operating Costs, and Revenues
Landfill Gas Recovery for LNG and CO2

RAW LFG CONSUMPTION(dry) 2.00 MM SCFD; 50% CH4

OPERATING PARAMETERS

Methane Recovery	73%
CO2 Recovery	52%
Onstream Factor, 350 days/year	96%

PRODUCT	PRICE
RLM	30 ¢/gallon
Liquid CO2	40\$/Ton
Power Required	774 Kw

CAPITAL COSTS

Installed

Equipment	Cost
Compressors	1,918,433
Storage Tanks	326,635
Columns	424,438
Vessels	233,221
Dehydration	112,849
Heat Exchangers	646,374
H2S Removal	105,953
Pumps	69,590

Capital Cost	<u>3,837,492</u>
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Contingency (18%)	<u>691,000</u>
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Total Capital Costs	4,528,492
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ANNUAL OPERATING EXPENSES

Electric Power	0.05 \$/Kw-hr	325,197
SulfaTreat		5,021
Labor (\$12/hr, 2 operators/day)		67,000
Labor Overhead (100% of labor)		67,000
Maintenance Materials (2% of capital)		91,000
Maintenance Labor (3% of capital)		136,000
Taxes & Insurance (1.5% of capital)		<u>68,000</u>

Total Operating Costs	759,000
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ANNUAL INCOME

	Amount	Daily	Annual
RLM	8,726 GPD	2,618	916,000
CO2	30 TPD	<u>1,190</u>	<u>417,000</u>
Total Income		3,808	1,333,000

PAYBACK PERIOD

7.9 Years

ACRION TECHNOLOGIES

Table B-3.1-2
Capital, Operating Costs, and Revenues
Landfill Gas Recovery for LNG and CO2

RAW LFG CONSUMPTION(dry) 2.00 MM SCFD; 50% CH4

OPERATING PARAMETERS

Methane Recovery	73%
CO2 Recovery	52%
Onstream Factor, 350 days/year	96%

PRODUCT	PRICE
RLM	30 ¢/gallon
Liquid CO2	40\$/Ton
Power Generated	774 Kw

CAPITAL COSTS	Installed Cost
Equipment	Cost
Compressors	1,918,433
Storage Tanks	326,635
Columns	424,438
Vessels	233,221
Dehydration	112,849
Heat Exchangers	646,374
H2S Removal	105,953
Pumps	69,590
Power Generation	510,955
Capital Cost	4,348,447
Contingency (18%)	783,000
Total Capital Costs	5,131,447

ANNUAL OPERATING EXPENSES

Electric Power	0.05 \$/Kw-hr	0
SulfaTreat		5,021
Labor (\$12/hr, 2 operators/day)		67,000
Labor Overhead (100% of labor)		67,000
Maintenance Materials (2% of capital)		103,000
Maintenance Labor (3% of capital)		154,000
Taxes & Insurance (1.5% of capital)		77,000
Total Operating Costs		473,000

ANNUAL INCOME	Amount	Daily	Annual
RLM	8,726 GPD	2,618	916,000
CO2	30 TPD	1,190	417,000
Total Income		3,808	1,333,000

PAYBACK PERIOD 6.0 Years

ACRION TECHNOLOGIES

Table B 3.1-3
Capital, Operating Costs, and Revenues
Landfill Gas Recovery for LNG and CO2

RAW LFG CONSUMPTION(dry) 3.50 MM SCFD; 50% CH4

OPERATING PARAMETERS

Methane Recovery	73%
CO2 Recovery	52%
Onstream Factor, 350 days/year	96%

PRODUCT	PRICE
RLM	30 ¢/gallon
Liquid CO2	40\$/Ton
Power Required	1355 Kw

CAPITAL COSTS

**Installed
Cost**

Equipment	
Compressors	2,683,919
Storage Tanks	456,968
Columns	593,795
Vessels	326,280
Dehydration	157,878
Heat Exchangers	904,288
H2S Removal	148,229
Pumps	97,358

Capital Cost	5,368,715
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Contingency (18%)	966,000
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Total Capital Costs	6,334,715
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ANNUAL OPERATING EXPENSES

Electric Power	0.05 \$/Kw-hr	569,095
SulfaTreat		8,787
Labor (\$12/hr, 2 operators/day)		67,000
Labor Overhead (100% of labor)		67,000
Maintenance Materials (2% of capital)		127,000
Maintenance Labor (3% of capital)		190,000
Taxes & Insurance (1.5% of capital)		95,000

Total Operating Costs	1,124,000
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ANNUAL INCOME

	Amount	Daily	Annual
RLM	15,270 GPD	4,581	1,603,000
CO2	52 TPD	2,083	729,000
Total Income		6,664	2,332,000

PAYBACK PERIOD

5.2 Years

ACRION TECHNOLOGIES

Table B-3.1-4
Capital, Operating Costs, and Revenues
Landfill Gas Recovery for LNG and CO2

RAW LFG CONSUMPTION(dry) 3.50 MM SCFD; 50% CH4

OPERATING PARAMETERS

Methane Recovery	73%
CO2 Recovery	52%
Onstream Factor, 350 days/year	96%

PRODUCT	PRICE
RLM	30 ¢/gallon
Liquid CO2	40\$/Ton
Power Generated	1355 Kw

CAPITAL COSTS

Installed

Equipment	Cost
Compressors	2,683,919
Storage Tanks	456,968
Columns	593,795
Vessels	326,280
Dehydration	157,878
Heat Exchangers	904,288
H2S Removal	148,229
Pumps	97,358
Power Generation	714,835
Capital Cost	6,083,549

Contingency (18%)	1,095,000
Total Capital Costs	7,178,549

ANNUAL OPERATING EXPENSES

Electric Power	0.05 \$/Kw-hr	0
SulfaTreat		8,787
Labor (\$12/hr, 2 operators/day)		67,000
Labor Overhead (100% of labor)		67,000
Maintenance Materials (2% of capital)		144,000
Maintenance Labor (3% of capital)		215,000
Taxes & Insurance (1.5% of capital)		108,000
Total Operating Costs		610,000

ANNUAL INCOME

	Amount	Daily	Annual
RLM	15,270 GPD	4,581	1,603,000
CO2	52 TPD	2,083	729,000
Total Income		6,664	2,332,000

PAYBACK PERIOD

4.2 Years

ACRION TECHNOLOGIES

Table B 3.1-5
Capital, Operating Costs, and Revenues
Landfill Gas Recovery for LNG and CO2

RAW LFG CONSUMPTION(dry) 5.00 MM SCFD; 50% CH4

OPERATING PARAMETERS

Methane Recovery	73%
CO2 Recovery	52%
Onstream Factor, 350 days/year	96%

PRODUCT	PRICE
RLM	30 ¢/gallon
Liquid CO2	40\$/Ton
Power Required	1936 Kw

CAPITAL COSTS

Installed

Equipment	Cost
Compressors	3,324,379
Storage Tanks	566,014
Columns	735,492
Vessels	404,140
Dehydration	195,552
Heat Exchangers	1,120,077
H2S Removal	183,601
Pumps	120,590

Capital Cost	6,649,844
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Contingency (18%)	1,197,000
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Total Capital Costs	7,846,844
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ANNUAL OPERATING EXPENSES

Electric Power	0.05 \$/Kw-hr	812,993
SulfaTreat		12,553
Labor (\$12/hr, 2 operators/day)		67,000
Labor Overhead (100% of labor)		67,000
Maintenance Materials (2% of capital)		157,000
Maintenance Labor (3% of capital)		235,000
Taxes & Insurance (1.5% of capital)		118,000

Total Operating Costs	1,470,000
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ANNUAL INCOME

	Amount	Daily	Annual
RLM	21,814 GPD	6,544	2,290,000
CO2	74 TPD	2,976	1,042,000
Total Income		9,520	3,332,000

PAYBACK PERIOD

4.2 Years

ACRION TECHNOLOGIES

Table B-3.1-6
Capital, Operating Costs, and Revenues
Landfill Gas Recovery for LNG and CO2

RAW LFG CONSUMPTION(dry) 5.00 MM SCFD; 50% CH4

OPERATING PARAMETERS

Methane Recovery	73%
CO2 Recovery	52%
Onstream Factor, 350 days/year	96%

PRODUCT	PRICE
RLM	30 ¢/gallon
Liquid CO2	40\$/Ton
Power Generated	1936 Kw

CAPITAL COSTS	Installed
Equipment	Cost
Compressors	3,324,379
Storage Tanks	566,014
Columns	735,492
Vessels	404,140
Dehydration	195,552
Heat Exchangers	1,120,077
H2S Removal	183,601
Pumps	120,590
Power Generation	885,415
Capital Cost	7,535,259
Contingency (18%)	1,356,000
Total Capital Costs	8,891,259

ANNUAL OPERATING EXPENSES

Electric Power	0.05 \$/Kw-hr	0
SulfaTreat		12,553
Labor (\$12/hr, 2 operators/day)		67,000
Labor Overhead (100% of labor)		67,000
Maintenance Materials (2% of capital)		178,000
Maintenance Labor (3% of capital)		267,000
Taxes & Insurance (1.5% of capital)		133,000
Total Operating Costs		725,000

ANNUAL INCOME	Amount	Daily	Annual
RLM	21,814 GPD	6,544	2,290,000
CO2	74 TPD	2,976	1,042,000
Total Income		9,520	3,332,000

PAYBACK PERIOD

3.4 Years

ACRION TECHNOLOGIES

Liquefied Natural Gas - LNG - CNG - NGV - Alternative Fuels - Vehicles - LCNG - CCNG - Clean Air - Global Warming

~ Description of the CH·IV LNG Dispenser ~

Transparency in LNG Vehicle Fueling with CH·IV!

The following is a discussion and description of the CH·IV LNG Dispensing system.

DISCUSSION

The idea of public access, self-serve LNG fueling has been viewed by many as impractical and possibly unreliable due to the level of training typically required to operate an LNG fueling system. CH·IV approached the issue of LNG fueling from a different perspective than previous participants. CH·IV approached it from the end-user perspective and then applied LNG technology to achieve fueling "transparency" with diesel through our patented design. CH·IV's technology base grew out of the world-wide trade of LNG and built off the expertise of its president, Jeff Beale, who has over 20 years of experience in the LNG industry.

LNG has many similarities to the other common cryogenic liquids like liquid nitrogen and oxygen, but a multi-component paraffin hydrocarbon has subtle differences that must be recognized. It is the recognition of these differences that lead to the design of our "self-serve" system. "Self-serve" means that the refueler need not know the condition of the vehicle tank he is about to fill or make any decisions relative to tank pressure, fuel level, or other tank conditions. Another major focus in the design was to make LNG fueling "look" and "feel" as close to gasoline and diesel refueling as possible. To achieve success, CH·IV utilized -

- a patented, single-hose LNG dispenser design;
- a scaled-down version of a large LNG pump;

- advanced control logic; and
- a novel vehicle vapor reliquefaction design.

It is often said that, "perception is reality." The picture below shows two LNG vehicles being fueled with a CH·IV dispensing system. This picture speaks volumes as to both the perception and reality of the CH·IV self-serve dispenser. The dispenser pictured is located at a publicly-accessible fueling island at a convenience mart that also has gasoline and diesel fueling islands. The value of "self-serve" would seem self-evident, however, a few words comparing the design and operation of our system with diesel from three perspectives may help clarify some of its uniqueness:

Driver/Hostler Perspective

Looking first at how diesel is handled: The vehicle arrives at the fueling island where the engine is shut off. Often a magnetic card reader is used to access the fuel dispenser. The driver or the hostler inserts or connects the fuel nozzle. Fueling commences. Little thought is given to the quality of the fuel as diesel has fairly tight specifications. The fueling is automatically terminated when a full tank is indicated. The driver or hostler removes the fuel nozzle and retrieves the receipt or logs the fuel consumption.

The diesel refueling scenario plays out almost identically for LNG. Specifically, a full tank means a full tank. Granted, the hostler handling LNG may wear more protective clothing than his diesel counterpart, but otherwise the rest of the refueling is virtually identical right down to the single hose and the "dry break" connection. Knowledge of the fuel quality of LNG is a non-issue as it is for diesel. LNG is delivered from liquefaction facilities having known fuel quality.

Equipment Perspective

Because of environmental concerns, new diesel fueling stations in many states are required to be built as "total containment." This means the storage tanks are double-walled with spill and leak detection. The connecting piping is provided with containment to direct any spillage or leakage away from potentially hazardous areas. On-line inventory monitoring and storage tank leak detection are becoming common place. The fuel pump has been removed from the fuel dispenser and integrated into the storage system. Dry break nozzles are becoming the norm for many diesel operations. Generally, diesel refueling means a card reader, a dispenser and the fuel nozzle, as it should be.

CH-IV's LNG tanks are always double-walled and spill containment for LNG piping is "standard." Just as with new diesel facilities, the CH-IV system provides for optional on-line monitoring of inventory and fuel composition. Our fuel pump is located very close to the storage tank(s). The nozzles used in LNG fueling are dry-break, as well. Just as with traditional motor fuels, the only operator involvement with a CH-IV LNG-based system is the card reader, the dispenser and the fuel nozzle.

Station Owner/Fleet Manager Perspective

Why does one own a fueling facility? To sell fuel or support a fleet. The refueling equipment is the means to the end; not the end. The simpler the system, the more desirable the system. Simplicity means less employee training, less reliability concerns, less hassle. These are the dimensions that are important to the station operator. This is the environment in which he is used to operating. What he doesn't want is equipment that he has to "pay attention to," a "highly trained staff," or inaccurate inventory management.

So how does the CH-IV LNG Dispenser stack up to these needs? Simple equipment means unattended operation and responsive service. Simple means "self-serve." Simple also means SAFE!

OBJECTIVE

Provide an LNG Dispenser that very closely emulates diesel refueling from an end-user (driver) and station owner perspective.

PROCESS DESIGN

- Fully automated for unattended operation
- 25 - 40 gpm pump transfer operation
- Single 25 - 40 gpm, single hose configuration dispenser with patent-pending nozzle "holstering" system
- Automatic hazard system detection and mitigation system
- Designed in compliance with:
 - NFPA 59A 1996 (Standards for the Production, Storage, and Handling of LNG)
 - NFPA 57 1996 (Standard for LNG Vehicular Fuel Systems)
 - Uniform Fire Code

OPERATION

- "Self-Serve" LNG fueling (no decision-making by refueler):
 - Automatically fuels vehicles that arrive with relatively high pressure in their tanks . . . even tanks close to (or at) their relief valve pressure setpoint
 - Automatically fuels vehicle tanks arriving with high nitrogen concentrations in their vapor ullage, such as new tanks being placed in service.
 - Automatically fuels vehicle tanks of different sizes
 - Automatically fuels warm vehicle tanks
- Single hose operation . . .
 - Never a need to connect a second "vent" hose to handle "special circumstances."

- Fueling hose is maintained without LNG present whenever being handled by driver (refueler)
- Simple!
- Patented-pending nozzle holstering system that integrates the nozzle holding and dispenser activation mechanisms
- Fail-safe operating mode

SAFETY FEATURES

- **LNG-FREE connect and disconnect.** CH-IV's patented dispenser design includes a most unique feature when compared to all other fueling technologies . . . the LNG fueling connection is purged of LNG before the driver has the opportunity to disconnect. The nozzle remains free of LNG when the next driver connects his vehicle. The lack of LNG present in the nozzle between fuelings means that frost build-up on nozzle is eliminated, or, at least, minimized.
- **Fail-safe emergency shut-down (ESD).** The ESD system can be activated by the driver, hose break-away (see below), gas detection, low temperature (optional), and fire detection (optional).
- **Hose breakaway protection.** Hose breakaway can be detected by any of three ways: excessive strain on dispenser, high flow and low pressure, any of which will activate an ESD.
- **Single-hose connection.** Simplifies handling of hoses. Minimized interface with the LNG system.
- **Self-contained LNG pump.** No exposed seals on rotating shafts. No exposed tubing as on "seal-less" pumps. Continuously cold, no thermal cycling (and stressing) of pump.
- **Vacuum-jacketed fueling hose.** This design minimizes frosting of hose and fueling nozzle, eliminating the need for heavy, bulky "cryogenic" gloves to fuel vehicle.

CH-IV LNGV SYSTEM ADVANCES

Overview

This section summarizes specific natural gas vehicle system enhancements that are integrated into the CH-IV LNG dispenser. The current design is based on the 25 - 40 gpm LNG dispenser developed for the U.S. Department of Defense Advanced Research Projects Agency (ARPA). This design built upon the configuration of the LNG fueling station CH-IV designed and installed in Bloomfield, New Mexico (pictured on Page 1). Besides being the FIRST "self-serve" LNG fueling station, there were a number of other "firsts" established:

- First truly single hose LNG fueling installation (no second [or coaxial] vapor return line).
- First, an only, LNG-free connect-disconnect dramatically reducing personnel exposure to LNG leaks at the fueling dispenser.
- First LNG dispenser capable of fueling two vehicles (from same LNG pump).
- First system to be able to automatically cool-down and fill new, warm LNG fuel tanks.
- First use of vacuum-jacketed fueling hose.
- First "no cool-down, continuously cold" transfer system.
- First "hose break-away" shutdown system.

Central to the success of "self-serve" operation is the design basis that does not require

routine or continuous monitoring or control of the system. CH-IV integrated numerous safety and process monitors throughout the system. Another basic design philosophy was to keep the equipment simple and use advance control logic and software control. Each of the major components is highlighted starting below.

LNG pump

One of the biggest advances that CH-IV developed with Ebara International of Sparks, Nevada was the choice of the variable speed, multi-stage, vessel-mounted, submerged motor LNG pump. CH-IV's familiarity with these pumps in import/export service world-wide lead to this choice. Part of the design basis requires flexible "on-demand" refueling capability; one that does not require a cool-down period.

LNGV refueling dictates a pump that can meet the following performance criteria:

1. The pump must be able to deliver a wide range of pressures and flows to meet the variety of on-board vehicle LNG storage systems that will be encountered.
2. The pump must be capable of remaining in a cold stand-by mode to facilitate quick restarts.
3. The pump must be capable of pumping a saturated liquid (at its boiling point) with as little as a few feet of head, i.e., the liquid head in the storage tank.
4. The system design should prevent two-phase flow or entrained vapor from reaching the eye of the pump impeller and thus causing cavitation.

The CH-IV pump system provides an extremely large operating envelope designed not only to overcome some potentially very high LNGV tank pressures but also to circulate LNG at very low flows and pressures. The entire performance envelope has been verified through very sophisticated and elaborate testing done by pump manufacturer.

The CH-IV pump system possesses the following attributes and benefits:

- **Cold Stand-By** - In "on demand" refueling operations it is mandatory to maintain the pump system in a continuously cold mode to avoid cool-down delays. Our design allows for long periods of stand-by without encountering problems from ice build-up, condensation in the motor windings, or any cool-down. The vessel design allows for any heat to be rejected through thermal siphoning of the LNG.
- **Thrust Equalization Mechanism (TEM™)** - Centrifugal pumps, by their basic design, are notorious for generating thrust in the direction of the pump shaft. This thrust is the primary cause for pump bearing failure. The TEM™ is a hydraulic design that neutralizes the thrust allowing the integrated pump and motor to float on the bearings. This is what permits the pump to operate throughout the wide operating envelope.
- **Lower Required Net Positive Suction Head** - The pump vessel acts not only as a vapor disengagement vessel but also as a stilling well helping guarantee a stable liquid phase fluid to the impeller. The CH-IV system design resulted in a required net positive suction head down of inches not feet.
- **Safer Operation** - The pumps are fully submerged in the LNG vessel with no shaft seals, minimizing potential releases of flammable liquids or vapors. Furthermore, there are no exposed moving parts or tubing. Since the pump does not continually cycle between warm and cold ($DT \gg 300^{\circ}F$), there is much less chance that

- flanges will "open up" or piping will experience continuous thermal cycles.
- Lower maintenance - There are very few moving parts and no external support systems. The motor and the pump are direct-coupled with two bearing sets (each end of the motor shaft). Pump thrust is neutralized (greatly reducing bearing wear) through a thrust equalization mechanism. The constant cooling flow flushes any non-condensable gases from the system. The process fluid cools the motor windings keeping the motor's operating temperature within a few degrees of the process, prolonging motor life.
- Quiet Operation - Because the pump is enclosed in a separate, highly insulated vessel, noise from the pump is virtually unnoticeable.

LNG Dispenser

At the heart of CH-IV's LNG dispenser is its patented, single-hose design that takes the refueler out of the decision-making role typical of all other LNG fueling operations. The driver of the vehicle need only take the following steps to fuel the LNG vehicle:

- 1) Lift the nozzle retention handle and remove hose from the dispenser.
- 2) Insert fueling nozzle into LNG vehicle.
- 3) Move dispenser handle to the "ON" position.
- 4) Wait for fueling to complete.
- 5) Return nozzle to dispenser and move nozzle handle to the "OFF" position.

The only action the driver can take is to initiate an emergency shutdown (ESD) by hitting the push-button on the face of the dispenser. The driver need not be concerned about the vehicle tank pressure or level. The dispenser will even cool-down warm or empty tanks automatically. Any non-condensable nitrogen in the tank will automatically be vented, as well. CH-IV also uses a first-of-its-kind breakaway - automatic shutdown system should a driver attempt to drive away before disconnecting the fueling hose. (However, CH-IV recommends very strongly installing an ignition lock-out switch built into the fill door on the vehicle.) The CH-IV dispensing system also utilizes a vacuum-jacketed fueling hose to prevent weight increase and flexibility decrease due to ice build-up.

A Note on Automatic Vehicle Tank Cooldown

CH-IV has stressed numerous times above that our LNG dispensing system can cooldown warm tanks, new tanks filled with nitrogen, etc. A common response by some in the industry is "So what? How often is that going to happen?" That is our point completely. It may not occur very frequently, but when it does with anyone else's systems someone needs to be able to recognize the condition and change the normal fueling procedure to accommodate the occurrence. That means, someone must be trained to recognize this situation, which sometimes can be very subtle if the nitrogen has "boiled-off" the LNG inside the vehicle tank. Someone must be trained to modify the fueling procedure.

With the CH-IV, no one needs to be trained in such a way!

LNG FUELING

The LNG dispenser is designed to fuel at rates between 15 - 50 gallons per minute as specified by customer or magnetic card (key) information. Nominal expectation is that refueling will take about 4 to 5 minutes including connection, disconnection, and card lock operation. The system is continuously maintained in a fully cooled-down status never requiring "cool-down delays."

Sequence of events:

1. The driver parks his vehicle at the LNG dispenser and turns off motor.
2. He first swipes his fueling card through the cardlock system to gain access. This may also include logging odometer reading, etc.
3. He puts on whatever protective equipment is required for this particular site for LNGV refueling (CH-IV recommends a minimum of "work" gloves typical of diesel fueling.)
4. He next opens fuel filler door, if existing.
5. He removes the LNG fueling hose from the dispenser by pushing the dispenser handle forward to the "RELEASE" position. (Refer to picture at right for Parker-Hannifin design and bottom of page for Moog-Carter design).
6. He next connects the fuel nozzle to the vehicle.
7. Upon moving the dispenser handle to the "ON" position, fueling automatically commences.
8. The driver has no other activity until fueling is complete. He may, however, wish to check fluid levels or perform any of the other routine service activities. LNG transfer is made with no additional driver involvement.
9. At the conclusion of transfer the driver moves the dispenser handle to the "RELEASE" position.
10. He then disconnects the LNGV fueling nozzle, closes the vehicle fuel filler door and returns the hose to the dispenser holster and moves the dispenser handle to the "OFF" position.
11. The driver starts the engine and drives away.

Moog-Carter Nozzle Design

For more information, suggestions [e-mail us](#).

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Last updated: 11/04/98

Liquefied Natural Gas - LNG - CNG - NGV - Alternative Fuels - Vehicles - LCNG - CCNG - Clean Air

Design and Operation of 'Self-Serve' LNG Fueling Stations

By Jeff Beale, CH-IV Cryogenics

INTRODUCTION

In September of 1995, CH-IV Cryogenics of Lawrence, Massachusetts, USA installed the first open public access, "self-serve" LNG vehicle fueling station. The station, as shown in the picture below, is part of a convenience store location in Bloomfield, New Mexico that also fuels gasoline and diesel vehicles. It is expected by the time of this conference that almost 4,000 vehicle fuelings will have been accomplished by the vehicle drivers since start-up. The idea of public access, self-serve LNG fueling has been viewed by many as impractical because of the level of training typically required to operate an LNG fueling system. CH-IV approached the issue of LNG fueling from a perspective of conventional fueling and an in-depth knowledge of LNG technology.

Two LNG Vehicles Fueling In Bloomfield

LNG has many similarities to the other common cryogenic liquids like liquid nitrogen and oxygen, but this multi-component cryogenic liquid has subtle differences that must be recognized. It was the recognition of these differences that lead to the design of the system in Bloomfield. Another major focus in the design was to make LNG fueling "look" and "feel" as close to gasoline and diesel refueling as possible. To achieve success, CH-IV developed a patented, LNG dispenser design utilizing its "single hose" technology; a scaled-down version of a large LNG pump; advanced control logic; and a unique vacuum-jacketed LNG transfer system. This paper will discuss each of these advances and provide an overview of the operation and design of the LNG dispensing system.

LNG FUELING SYSTEM OVERVIEW

The figure above shows a generic schematic of the system installed in Bloomfield. The major components are a 1,950 gallon Intermediate Tank; two, variable speed, multistage, vessel-mounted, submerged-motor LNG pumps; an LNG "conditioning" system; the Tri-Vac LNG transfer system; and the two-vehicle LNG dispenser. The initial supplemental storage, in the case of the Bloomfield station, is a 10,500 gallon LNG transport trailer. However, one of the unique features of the Intermediate Tank design is that the supplemental storage can be any of a variety of types of cryogenic storage vessel(s). Types would include conventional horizontal or vertical LNG storage tanks, intermodal tanks, on-site liquefaction, and so on. This allows a station operator to "grow" his storage volume as station demand increases.

Operationally, there are five distinct modes of unmanned operation:

1. Tank-to-Tank Transfer is the batch make up of the Intermediate Tank which is scheduled during the "non-fueling" period.
2. LNG Conditioning (optional) takes place immediately following transfer. This is done in cases where a minimum equilibrium condition is desired that is higher than the equilibrium condition of the supplemental tank.
3. Idle status is maintained outside the "fueling period." In this condition, the system is maintained in a fully cooled-down condition and ready for start-up.
4. LNG Circulation is used during the fueling period which is defined by the station owner. LNG is circulated throughout the system at a very low flow.
5. LNGV Fueling is initiated upon approval of the card-lock system followed by connection of the dispenser nozzle to the vehicle. The Bloomfield station can fuel two vehicles from a single dispenser. Ability to expand to a second dispenser and simultaneous fueling of four vehicles has been provided.

The layout of the CH-IV LNG fueling station also supports its "transparency" with gasoline fueling as can be seen in the picture below.

LNG Dispenser at Convenience Store

The LNG tanks and pumps (shown in a picture below) can be located far from the fueling island. In the case of Bloomfield the separation distance is about 75 feet. The tank and pump modules are surrounded by a latticed, chain link fence further taking the LNG equipment out of the sightline of the vehicle driver.

LNG tank/pump area

The sketch at right highlights a generic LNG station. Obviously, the choice of supplemental storage, number of dispensers and general station layout will affect the final configuration. The Tri-Vac Transfer System (described below) is routed in an open, grated trough that runs just below grade to the fueling island. This troughing is also designed to direct any LNG spill, however remote the potential, away from the fueling island and the vehicles.

**TYPICAL CH-IV FUELING
STATION LAYOUT**

LNG STORAGE TANK

The 1,950 gallon vertical tank is double-walled and perlite insulated, the so-called "Intermediate tank." The tank deviates from "standard" cryogenic storage tank design by utilizing proprietary nozzle configurations that facilitate liquid and vapor handling associated with vehicle fueling. It is the Intermediate Tank that allows for the flexibility in choices of supplemental storage.

LNG PUMPS

One of the biggest deviations from other LNG vehicle fueling stations is CH-IV's choice of the Ebara Cryodynamics variable speed, multi-stage, vessel-mounted, submerged motor LNG pump. CH-IV's familiarity with these pumps in import/export service world-wide lead to this choice. Part of the design basis required flexible "on-demand" refueling capability; one that does not require a cool-down period. The pump also provides an extremely large operating envelope designed not only to overcome some potentially very high LNGV tank pressures but also to circulate LNG at very low flows and pressures. The entire performance envelope, including its extremely low net positive suction head, was verified through very elaborate testing at Ebara's Sparks, Nevada manufacturing and test facility.

The pump, shown in the picture at left, sits within the suction vessel. Motor cooling and bearing lubrication are provided by directing a small amount of the discharge flow through and around the motor and

bearings and returning this flow to the suction. A vent line provides the path for the removal of any vapor bubbles.

The pump possesses the following attributes and benefits:

- **Cold Stand-By** - In refueling operations it is desirable to maintain the pump system in a continuously cold mode to avoid cool-down delays. Our design allows for long periods of stand-by without encountering problems from ice build-up, condensation in the motor windings, or any cool-down.
- **True Variable Speed Operation** - The pump utilizes a variable speed driver that can vary the pump speed over its substantial operating envelope.
- **Pump Thrust Neutralization** - Centrifugal pumps, by their basic design, are notorious for generating thrust in the direction of the pump shaft. This thrust is the primary cause for pump bearing failure. Ebara's pump design neutralizes this thrust allowing the integrated pump and motor to "float" on the bearings, which permits the pump to operate throughout the wide operating envelope.
- **Very Low Required Net Positive Suction Head** - The pump vessel acts not only as a vapor disengagement vessel but also as a stilling well helping guarantee a stable liquid phase fluid to the impeller. This pump, verified by testing, has a required net positive suction head of inches not feet.
- **Safer Operation** - The pumps are fully submerged in the LNG vessel with no shaft seals, minimizing potential releases of flammable liquids or vapors. Furthermore, there are no exposed moving parts or tubing. Since the pump does not continually cycle between warm and cold (differential temperature > 300°F), there is much less chance that flanges will "open up" or piping will experience continuous thermal cycles.
- **Lower maintenance** - There are very few moving parts and no external support systems. The motor and the pump are direct-coupled with two bearing sets (each end of the motor shaft). Pump thrust is neutralized (greatly reducing bearing wear) through a thrust equalization mechanism. The constant cooling flow flushes any non-condensable gases from the system. The process fluid cools the motor windings keeping the motor's operating temperature within a few degrees of the process, thus prolonging motor life.
- **Quiet Operation** - Because the pump is enclosed in a separate, highly insulated vessel, pump noise is virtually unnoticeable.

LNG DISPENSER

At the heart of CH-IV's LNG dispenser is its patented single-hose design that takes the refueler out of the decision-making role typical of all other LNG fueling operations. A close-up of the Bloomfield dispenser is shown at right. The dispenser displays total price, gallons dispensed, and price per gallon. Much as with gasoline or diesel, there are now "special" instructions to follow to activate the dispensing system. There is no "second" hose for vehicle tank depressuring.

The driver of the vehicle need only take the following steps to fuel the LNG vehicle:

1. Lift lever and remove fueling nozzle from the dispenser (See picture at right)
2. Insert fueling nozzle into LNG vehicle
3. Wait for fueling to complete as indicated by a bell
4. Lift lever and return nozzle to dispenser

The only other action the driver can take is to initiate an emergency shutdown by hitting the push-button on the upper left face of the dispenser (as shown in picture of dispenser). The driver need not be concerned about the vehicle LNG tank pressure or level. The dispenser will even cool-down warm or empty tanks automatically. Any non-condensable nitrogen in the tank will automatically be vented, as well. The CH-IV dispenser also incorporates a first-of-its-kind breakaway - automatic shut-down system should a driver attempt to drive away before disconnecting the fueling hose. The CH-IV dispensing system also utilizes a vacuum-jacketed fueling hose to prevent weight increase and flexibility loss due to ice build-up.

The system at Bloomfield can fuel two vehicles at 12 gallons per minute. By the time of this conference, CH-IV will have installed a single vehicle, 30 to 50 gpm dispenser in Denver, Colorado as part of an Advanced Research Projects Agency (ARPA) contract. Also under development is a two-vehicle, 30 GPM dispenser.

LNG "CONDITIONING" SYSTEM

The state-of-the-art of some natural gas vehicle engines require fuel gas pressures higher than the equilibrium pressure of LNG when first delivered from the liquefaction source. As an alternative to incorporating a fuel pump on-board the vehicle, increasing the saturated condition of the LNG will often meet the fuel gas requirement. This is often referred to as "conditioning" the LNG. A simple

way to condition the LNG is to pass some or all of the pump discharge through a heat exchanger. The goal is not to vaporize the LNG, but to increase its liquid temperature which also increases its equilibrium pressure. The CH-IV system provides this option as part of normal station operation.

TRI-VAC LNG TRANSFER SYSTEM

One of the major challenges faced by physically separating the pumps from the dispenser was how to control both the cost and heat leak into the connecting piping. Multiple cryogenic pipes are required to support the two-vehicle dispenser. The CH-IV system uses a new design that addresses both of these challenges. The actual length of piping distance in Bloomfield is almost 100 feet from the pump area to the dispenser. The Tri-VacTM system was pre-fabricated off-site and installed in just a few hours. The Tri-Vac lays in the rough seen in the "LNG Dispenser at Convenience Store" picture above.

SUPPLEMENTAL STORAGE

LNG storage tanks are the biggest single cost item when installing an LNG fueling system. Station owner/operators are often faced with deciding between installing a small tank initially to coincide with start-up requirements and then be faced with replacing the tank with a more appropriately sized tank later. This is not only costly, but it can interrupt fueling for an extended period of time. The Intermediate tank concept borrows from typical industrial chemical "day tank" operation and eliminates this problem. The Intermediate Tank can draw its supply from virtually any cryogenic storage vessel. This would include conventional horizontal or vertical storage tanks, ISO 9000 intermodal tanks, LNG transport trailers, or on-site liquefaction. The Bloomfield station initially used a 10,500 gallon LNG trailer that served as both storage and transport vehicle.

UNMANNED OPERATION

Central to the success of the Bloomfield operation is the design basis that does not require routine or continuous monitoring or control of the system. CH-IV integrated numerous safety and process monitors throughout the system. Another basic design philosophy was to keep the equipment simple and use advanced control logic and software control. Through conventional computer modem access CH-IV can monitor this station's operation, download historical operating data or perform manual control of the station. For example, following an extended fuel supply interruption it became necessary to re-cooldown the Intermediate Tank. The cooldown operation was accomplished from our Massachusetts office 2,400 miles away using local support performing visual inspection only.

SUMMARY

CH-IV Cryogenics believes that for LNG to become the alternative fuel of choice it has to be moved from the perception of exotic and "special" to the reality of commonplace. The Bloomfield station and the heavy-duty LNG dispenser are providing the LNGV industry with witness to the simplicity and safety with which LNG vehicles can be fueled.

For more information, suggestions [e-mail us](#).

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dealer

Model 320 (refuse truck chassis), Peterbilt Motors Company
Peterbilt's Model 320 is available in a variety of cab configurations, including left-hand, right-hand, or dual-drive with right-hand stand up. Cost: \$120,000 -- Where To Buy: Visit Peterbilt website for local

Severe-Duty Heavy Truck Chassis, Freightliner Corporation
The Freightliner Corporation uses the Cummins L10G, Detroit Diesel Series 50G, and Caterpillar 3306G & 3406G engines for the various models of LNG-fueled class8/severe-duty heavy truck chassis. Cost: Varies depending upon engine and fuel options -- Where To Buy: Contact manufacturer for local dealer

T800 112, Kenworth Truck Company
The Kenworth Truck Company's Liquefied Natural Gas T800 is a heavy duty truck featuring a 300hp engine and ten speed transmission. Cost: Call for quote -- Where To Buy: Contact manufacturer for local dealer

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Market Barriers & Opportunities

Barriers to Alternative Fuel Trucks

The following are some of the most important vehicle and fuel related market barriers to the successful use of alternative fuel heavy-duty vehicles on the Interstate Clean Transportation Corridor:

1. There is a lack of commercially available OEM alternative fuel heavy-duty trucks;
2. Operators are discouraged by the higher cost of clean alternative fuel vehicles in comparison to conventional diesel vehicles;
3. There is uncertainty over resale values of alternative fuel heavy-duty trucks;
4. There is uncertainty with respect to engine durability, maintenance costs, engine rebuild prospects for alternative fuel heavy-duty engines;
5. There is a perception that various performance penalties are associated with alternative fuel truck technologies, e.g., reduced torque, power, mileage, range, durability, etc.;
6. There is uncertainty whether weight and space penalties associated with some alternative fuel systems will adversely affect truck payload capacity;
7. There is a shortage of conveniently located publicly accessible fueling outlets;
8. There is uncertainty with respect to commitment of fuel suppliers to consistently provide fuel;
9. Conversely, there is uncertainty with respect to the market demand for alternative fuel;
10. The tax structure now penalizes one alternative fuel severely;
11. The capital costs of fuel infrastructure development or fuel delivery can be very high for some fuels;
12. There is uncertainty with respect to long term prices for alternative fuels;
13. There are perceptions of safety problems with respect to some alternative fuels.
14. Alternative fuels may require additional training for truck operators, fuel handlers, mechanics, and emergency service personnel.
15. New technologies may be subject to inappropriate standards, codes, and regulations.
16. There are risks of orphaned investment if one chooses the wrong technology or fuel to invest in.
17. There is uncertainty about consistent fuel quality.

1. Lack of Commercially Available OEM Alternative Fuel Heavy-Duty Trucks

Truck fleet operators complain that there is insufficient alternative fuel heavy-duty truck product available to meet their needs. Unfortunately, this complaint is well-founded with respect to all alternative fuels. However, the situation has improved significantly with respect to some truck technologies, particularly those powered by natural gas. Some engine manufacturers have made significant investments in heavy-duty natural gas engines and have improved their performance characteristics. Several companies, including Detroit Diesel, Cummins Engines, and Caterpillar, now offer either dedicated or dual fuel (w/diesel) natural gas engines.

However, vehicle manufacturers are generally separate enterprises from engine manufacturers and these manufacturers have been slower to design and build trucks for these engines. In addition,

components, such as properly designed on-board fuel storage equipment, present engineering challenges which increase the costs of the vehicles. Vehicle manufacturers also feel compelled to provide special support services, such as mechanics training, to the alternative fuel vehicle customer, creating added incremental costs.

Availability of Alternative Fueled Heavy-Duty Trucks for Line Haul Applications

<i>CNG</i>	There are a wide variety of CNG engines available from a number of manufacturers. Only the fuel system distinguishes CNG and LNG engines. For the line haul operations relevant to the <i>ICTC</i> , however, truck operators say that CNG has important limitations. With roughly a quarter of the energy density of diesel fuel, and half that of LNG, more fuel tanks are required to achieve comparable range objectives. These tanks add weight and are likely to encroach on space available for cargo. Using fewer fuel tanks means that CNG trucks will have significantly reduced range. As a result, CNG trucks are typically light- and medium-heavy-duty vehicles that are powered with engines < 300hp, carry smaller payloads and have shorter range requirements.
<i>LNG</i>	The limitations on CNG trucks means that line haul truck operators interested in natural gas are likely to prefer LNG as a fuel. The difference between trucks operating on CNG and LNG is the fueling system. CNG systems require high pressure fuel lines and storage cylinders while LNG systems require cryogenic fuel lines and storage cylinders. Several vehicle manufacturers are prepared to take orders and deliver OEM LNG trucks today. According to the California Trucking Association, Kenworth will deliver fully integrated LNG trucks for heavy-duty applications using the 350 hp Cummins L10 series engine. Later this year, Freightliner will have an LNG truck available which will use the 400 hp Detroit Diesel Series 60 engine. (The smaller Detroit Diesel Series 50 is regarded as suitable for transit and intra-urban applications, rather than long haul applications.)
<i>Methanol</i>	Methanol showed early promise as an alternative fuel for heavy-duty applications. While the Detroit Diesel 6V-92 engine is available, there are no vehicle manufacturers currently producing methanol-powered product for the heavy-duty truck marketplace. The high price of methanol fuel has proven the essential barrier to the entry of methanol as a competitive fuel in heavy-duty applications.
<i>Ethanol</i>	While ethanol is heavily used in light duty vehicles in some countries there are no heavy-duty truck engine or vehicle manufacturers designing or manufacturing ethanol powered product for the American market. Ethanol advocates are currently seeking a role in the transit bus market, but are essentially focused upon the conversion of methanol buses, e.g., at the Los Angeles County Metropolitan Transportation Authority.
<i>Propane</i>	While some manufacturers offer LPG engines for light, medium, and light-heavy-duty applications, there are currently no manufacturers producing vehicles powered by propane for the heavy-duty truck marketplace. Caterpillar offers a propane version of its 300 hp 3306 engine. There are other engines in development, some showing favorable emissions

	performance, but none are commercially available. Orange County Transit Authority has had success operating optimized LPG buses, including very effective emissions reductions performance.
Electric	Hybrid-electric and fuel cell powered trucks are conceptually promising for many heavy-duty applications, but there are no manufacturers producing heavy-duty product for the commercial truck market. Ballard Power, Vancouver, B.C., and H-Power anticipate marketing fuel cell powered transit buses sometime before the turn of the century, but there is much work to be done before this technology will be used in commercial trucking applications.
Biodiesel	Because of the high costs of biodiesel fuels and the challenges associated with assuring reliable engine operations, there are no engine or vehicle manufacturers with active programs to design and produce heavy-duty trucks operating on biodiesel. Conversions and/or retrofits are fairly simple and cheap. These fuels show some emission reduction promise in engines designed to operate on a blend of diesel and biodiesel fuels.
Diesel/ Water Emulsions and Mixtures	Diesel/water emulsions and mixtures show promise as a cleaner heavy-duty truck technology than conventional diesel. Demonstration projects are underway investigating the durability and performance characteristics of these technologies, but as yet there are no commercial manufacturers designing and producing these vehicles commercially. Caterpillar hopes to have commercially available product soon. The Department of Energy indicates that emulsified diesel does not qualify as an alternative fuel.
DME	Dimethyl Ether offers yet another way to use natural gas in a heavy-duty vehicles. Navistar is currently working on suitable engine modification which would allow heavy-duty engines to use DME.

2. Operators are Discouraged by the Higher Cost of Clean Alternative Fuel Vehicles in Comparison to Conventional Diesel Vehicles

Since no manufacturer now produces long haul heavy-duty trucks powered by alternatives other than natural gas, the only information available for comparison purposes pertains to LNG powered trucks. As a result of low levels of production and the need to re-engineer chassis and fuel systems to be compatible with the engine, prices for heavy-duty LNG trucks remain high, relative to conventional diesel technology. Class 8 long haul diesel trucks average from \$65,000 - \$75,000 per truck when larger orders are made. The comparable Cummins/Kenworth LNG heavy-duty truck costs over \$100,000 per vehicle, although typically these vehicles are only available in the 65,000 lbs. gvwr, range rather than the 80,000 lbs. gvwr preferred by most long haul operators. Of this \$25,000 to \$35,000 incremental cost, most is attributable to the fueling system, the need for cryogenic fuel tanks, and additional warranty cushion. For trucking operators this incremental cost is a very steep penalty to overcome.

3. Uncertainty Over Resale Values of Alternative Fuel Heavy-Duty Trucks

The value of used vehicles on the resale market is a significant element in investment decisions made by truck operators. Heavy-duty diesel trucks have well established resale markets and reasonably predictable values on that market. Typically, a diesel truck purchased for \$65,000 will sell in five years on the used truck market for about \$25,000. However, buyers of alternative fuel trucks cannot

yet assume a resale market for their trucks, and for accounting and investment purposes must assume a resale value of zero. This is essentially equivalent to adding another \$25,000, for example, to the purchase price of LNG vehicles relative to diesel vehicles.

4. Uncertainty with Respect to Engine Durability and Engine Rebuild Prospects for Alternative Fuel Heavy-Duty Engines

It is customary for truck operators to anticipate the useful life of a conventional heavy-duty diesel vehicle to be in the neighborhood of 30 years, with regular engine rebuilds every 400,000 - 700,000 miles, roughly every four years, although as often as once a year for some trucks operators. Generally, major line haul operators will use a new truck for 4 or 5 years before selling it on the used truck market.

Such predictability is a function of a mature industry operating many vehicles over many years and many road miles, generating sufficient experience and technological refinements to permit reasonably predictable durability and manufacturer warranties which reflect that expectation. This allows the significant capital investment decisions required in the purchase of new trucks to be made in an atmosphere of confidence rather than uncertainty.

The lack of experience with alternative fuel heavy-duty trucks means that the trucking industry is unable to predict their durability with confidence, or to predict their rebuild cycles or their useful life. Operators will be reluctant to make major capital investments in the absence of this predictability.

5. Perception that Performance Penalties are Associated with Alternative Fuel Truck Technologies, E.G., Reduced Torque, Power, Thermal Efficiency, and Fuel Economy, Etc.

The performance capabilities of heavy-duty technologies are a key element of market acceptance. This may be especially true in the case of the heavy-duty line haul trucks most frequently employed in interstate shipping where mileage, range, torque and power are key operational parameters and cost determinants. Industry perceptions that alternative fuel trucks get reduced mileage, and, therefore, use more fuel, necessitate more frequent fuel and service stops, or lack the torque and power of their diesel counterparts undermines market acceptance of alternative fuels in long haul shipping.

The following table compares the energy content of several fuels and the implications for the volume and weight of fuel storage on the vehicle. Energy content will be one critical indicator of expected mileage per comparable volume of fuel.

	Typical diesel	Methanol	Ethanol	LPG	CNG	LNG
Energy Content						
Btu/gal LHV	128,100	57,000	76,300	83,000	30,000*	73,000**
Relative fuel volume***	1	2.2	1.7	1.5	4.3	1.7
Relative full fuel tank weight	1	2.1	1.6	1.2	3.7	1.4

* at 3000 psig

** saturated liquid at 20 psig and -238 degrees Fahrenheit

*** for equivalent range, assuming all engines of equal thermal efficiency

Since LNG has less energy content per gallon than does diesel fuel, LNG powered vehicles have reduced mileage and, therefore, less range for equal fuel capacity when compared to a similar diesel powered truck with an engine of equivalent thermal efficiency. In general, LNG trucks will use roughly 2 gallons of fuel for every gallon consumed by a similar diesel truck. These factors will significantly affect fuel consumption costs and the frequency of stops required for refueling and service on a given route. LNG fuel prices must be very competitive in order to offset this operating disadvantage.

Demonstration projects can help to clarify relative performance by placing alternative fuel and diesel trucks into comparable operational circumstances. For example, demonstration projects designed to compare heavy-duty LNG trucks to heavy-duty diesel trucks are underway with Wal-mart and UNOCAL in association with Acurex Environmental. In the Wal-mart case a line haul LNG truck compared very favorably with a line haul diesel truck in terms of power, torque, acceleration, hill climbing ability, and mileage. In the case of UNOCAL, where the duty cycle was much more stop-and-go the LNG truck compared much less favorably on these same criteria.

Methanol, ethanol, and propane all have similar problems - lower energy content per given volume translates into reduced mileage and range, and more frequent stops, when used in trucks with engines of equivalent thermal efficiency. These factors all create competitive economic disadvantages for these fuels. These disadvantages can be offset if the price of the fuel is cheaper than diesel fuel, or exacerbated if the price of the fuel is more expensive than diesel fuel. It is expected that diesel-water emulsion technologies will also get significantly reduced mileage and range when compared to conventional diesel.

6. Uncertainty Whether Weight and Space Penalties Associated with Some Alternative Fuel Systems will Adversely Affect Truck Payload Capacity and Vehicle Range

Some alternative fuels, especially gaseous fuels like CNG, typically require a larger number of fuel tanks per vehicle to achieve a range comparable to that of diesel technologies. In general CNG trucks require approximately four times the fuel volume and almost four times the weight in fuel tanks as diesel trucks to get comparable range (see above figure). The added weight will decrease the range and the potentially lost space may reduce the payload of the vehicle and thus reduce its economic efficiency. Alternatively, manufacturers of CNG trucks may simply reduce the number of fuel tanks, thus reducing range of the vehicle but having less effect on the potential payload. This is the major reason why few operators envision CNG as relevant to long haul truck operations.

As the above chart demonstrates, there is some degree of weight and volume penalty, and therefore range and potential payload penalty, for all of the alternative fuels most commonly discussed in connection with heavy-duty trucks. With each these fuels, weight penalties may be addressed by carrying less fuel, thus directly reducing potential range. Liquid fuels with higher energy content, like ethanol, LNG or LPG, provide much less of a penalty than CNG; therefore, these fuels may be more

acceptable in some fleet applications.

Dual fuel technology requires two fueling systems and will suffer from space and weight penalties. Water emulsion systems will also carry extra water and will therefore bear a weight and some level of space penalty. The implications may not be significant for all carriers.

7. Shortage of Conveniently Located Publicly Accessible Fueling Outlets

Truck operators will not invest in alternative fuel vehicles unless they are assured of readily available fuel at conveniently designed facilities in accessible locations dispersed strategically along key routes. At this moment there are few alternative fuel facilities designed for servicing long haul trucks available along the *ICTC*.

There are a growing number of CNG facilities in Southern California and elsewhere, but few long haul trucks if any are expected to see CNG as a viable option for long haul trucks.

In California there are only a few LNG fueling sites - at Los Angeles International Airport (LAX), at a site in downtown Los Angeles, at a Union Pacific site in the Los Angeles area, and in Porterville, California, and a small site operated by Cummins West in West Sacramento. All are operated as private-access only facilities. LAX plans to install a larger public access station, and a public-access LNG fueling facility is planned for Ontario, California, which will be designed to meet the needs of heavy-duty trucks. There are several California communities which have indicated an interest in LNG fueling facilities in connection with the operation of alternative fuel refuse trucks. In addition JBK operates LNG fueling sites in San Manuel, Arizona, and Woods Cross, Utah.

Propane is widely available for recreational and other users but no facility exists specifically to serve long haul heavy-duty trucks. Methanol is available at about 50 sites in California, almost exclusively serving light- and medium-duty vehicles.

8. Uncertainty with Respect to Commitment of Fuel Suppliers to Consistently Provide Fuel

Strong evidence of a fuel supplier commitment is necessary to motivate truck operators to consider investment in vehicles. Truck operators currently perceive that the fuel supplier industry is unlikely to invest in the necessary facilities required to assure sufficient fuel supplies at practical intervals along the *ICTC* route. Efforts to gain the full participation of fuel suppliers in the development of heavy-duty fueling facilities has thus far been unsuccessful. Fuel suppliers seek a market demand of consistent fuel users approaching 50 to 100 heavy duty vehicles per station, a difficult threshold to achieve in a short time frame.

9. Uncertainty with Respect to the Market Demand for Alternative Fuels

Fuel suppliers see insufficient interest in the truck operator market to justify the risk of investment in alternative fuel facilities. Because of the very high capital costs associated with fueling facilities, investment requires a high level of certainty that there will be sufficient market demand for the fuel. Fuel suppliers must see strong evidence of a growing and committed market of truck operators ready to buy LNG before they will invest in facilities.

There is clearly a "chicken and egg" problem to be solved here. There needs to be an active "marriage broker" prepared to coordinate the efforts of both the fuel supplier and truck operator

industries in order to overcome these barriers. The inherent public interest in clean air and energy diversity suggests the public sector as the likely broker. Without disciplined public commitment stimulating private demand on the truck side and private supply on the fuel side, there is great uncertainty whether significant numbers of heavy-duty long haul alternative fuel trucks will be on the road creating demand for alternative fuels any time soon.

10. The Current Federal Tax Structure Penalizes Alternative Fuels, Particularly LNG, LPG, and Methanol, Rather than Encouraging them

Under current federal tax law, CNG is taxed at 4.854 cents per 100 standard cubic feet, LNG is taxed as a "special motor fuel" at 18.3 cpg, while diesel is taxed at 24.3 cpg. However, adjusting for energy content and assuming equivalent thermal efficiency, CNG is taxed at 6.7 cents per diesel equivalent gallon, and LNG is taxed at 31.3 cents per diesel equivalent gallon. As a result, current tax law actually penalizes LNG, compared to diesel fuel, despite its clear and significant environmental benefits.

LPG is also taxed as "special motor fuels" at a rate of 18.3 cpg. But, because of energy content differential, LPG is also, in effect, penalized by the structure of the tax code, paying an effective 27.4 cents per diesel equivalent gallon.

Methanol and ethanol are taxed at 12.3 cpg and 12.9 cpg respectively. This tax translates to 27.6 cpg and 21.6 cpg on a diesel equivalent basis. Thus methanol is also disadvantaged by the tax structure, though ethanol is not.

11. The Capital Costs of Fuel Infrastructure Development or Fuel Delivery can be Very High for Fuels Which Must be Compressed or Significantly Lowered in Temperature, Like Natural Gas

A major impediment to the development of an alternative fuel fueling infrastructure is the capital investment costs of creating the necessary facilities. For example, the capital investment required to build a 55,000 gallon LNG liquefaction facility, including storage tanks, assuming a ready supply of natural gas through an existing underground infrastructure, is nearly \$5 million dollars. Such a facility would have the capacity to fuel approximately 70 trucks per day, assuming 175 gallons of fuel per truck.

Most fuel suppliers will simply choose to deliver LNG to dispensing sites along the *ICTC* from existing liquefaction facilities located elsewhere in the U.S. such as Wyoming or Texas. While this strategy avoids significant initial capital outlay for the liquifier it nonetheless requires a capital investment in storage capacity and fuel delivery systems. However, the most significant costs would be that of fuel transport over many miles. For example, a single fuel truck carrying 10,000 gallons from Wyoming to Los Angeles would cost approximately \$3000 to \$4,000 or \$0.30 - \$0.40 per gallon of LNG.

In most cases, in order to create sufficient certainty of fuel sales it will be best to identify local heavy-duty LNG users, such as transit buses, refuse haulers, local truck fleets, railroads and the like, that can make significant fuel purchase commitments.

12. Uncertainty with Respect to Long Term Prices for Alternative Fuels

The lack of historical experience with alternative fuels in truck applications creates uncertainty about

its market dynamics. As a result, it is difficult to expect stability in fuel prices for some fuels, unless the vehicle market is a small part of a much larger market with stable market dynamics. However, recent price increases for diesel fuels have created new opportunities for alternative fuels despite these uncertainties.

13. Perceptions of Safety Problems with Respect to Some Alternative Fuels

Opponents of alternative fuels often say that there are greater safety risks associated with alternative fuels. It is sometimes suggested, for example, that pressurized or cryogenic fuels have greater risk of explosion, for example. While it is true that all fuels have special and distinctive handling needs, proponents claim that there is little evidence that alternative fuels are more risky than conventional fuels if stored and handled properly. These are issues which need clarification and resolution if alternative fuels are to be acceptable in the marketplace.

14. Alternative Fuels May Require Additional Training for Truck Operators, Fuel Handlers, Mechanics, and Emergency Response Personnel

15. New Technologies may be Subject to Inappropriate Standards, Codes, and Regulations

16. Risks of Orphaned Investment if one Chooses the Wrong Technology or Fuel in which to Invest

17. Uncertainty About Consistent Fuel Quality

Advantages of Alternative Fuel Trucks

While it is true that alternative fuels face very difficult market barriers, they also possess certain advantages in the marketplace, advantages which have become more evident as diesel prices have risen recently. Analysts say that diesel prices are not expected to come down significantly any time soon.

1. Avoid Dependence on a Single Fuel, Rising Diesel Prices

Lack of competition in the diesel fuel market has made truck operators very vulnerable to rapid increases in diesel fuel prices, as has been evidenced by recent price spikes. The development of competing alternative fuels promises to help keep fuel prices lower, and give operators choices.

2. Domestic Nature of the Fuel Avoids Risk of Fuel Price Spikes and Supply Disruptions Caused by International Events

Diesel fuel is derived from petroleum supplies. A tremendous percentage of our nation's diesel supply is refined from imported oil, although California diesel fuels are less reliant on foreign oil suppliers. In general, natural gas is supplied by domestic producers, as is ethanol and propane. As a result, these alternative fuels are not vulnerable to supply disruptions or price spikes occasioned by international incidents.

3. Potentially Lower Operating and Maintenance Costs

Transit agencies which use natural gas, such as Sacramento Regional Transit and Pierce Transit,

Tacoma, Washington, have experienced significantly lower operating costs in their CNG buses when compared to even their newest diesel buses. The lower costs are partly attributable to lower fuel costs. However, both fleets report lower maintenance costs as well. In general, operators say, crankcase oil stays cleaner and can be changed less frequently. These operators expect to be able to reduce the frequency and therefore the costs of regular engine rebuilds. While generalizing from transit fleets to truck fleets with very different engines, payloads, and duty cycles is not possible, these experiences are suggestive. It may be the case that truck operators will have similar experience with LNG versus diesel fuel.

4. Avoidance of Risks and Costs of Environmental Regulations

Truck operators which begin to integrate low emission alternative fuel trucks into their fleets are likely to be ahead of the regulatory curve and are less likely to be forced by regulatory mandate to introduce cleaner technologies on a less advantageous basis.

5. Public Relations Advantages of Clean Fuel Technologies

Fleet operators which integrate cleaner alternative fuel trucks into their fleets are likely to experience significant public relations advantages. Translating "good will" into dollars and cents is always unpredictable, yet it is certain to be of significant value for some fleets.

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Regulatory Barriers & Opportunities

1. National Regulatory Environment

National Deregulation of Trucking

Since August, 1994, the Interstate Commerce Commission (ICC) no longer regulates many aspects of interstate common carrier trucking operations, including rates, services, and routes. Effective January 1, 1995, laws adopted by Congress has preempted each state's ability to regulate price, routes, and services of all motor carriers, except household goods and haulers of recycled items and hazardous wastes. Despite this preemption, all intrastate trucking companies will still have to register with states and meet safety and liability insurance requirements.

Industry publications suggest the prospect exists for a complete deregulation of the trucking industry, including the possible abolition of the ICC.

Clean Air Act

National emissions standards for a variety of classes of heavy-duty trucks are set by the U.S. Clean Air Act. Currently, new heavy duty vehicles must meet a NOx emissions standard of 5.0 g/bhp-hr. This standard advances to 4.0 g/bhp-hr in 1998.

The United States Environmental Protection Agency (EPA) has the authority to adopt more exacting standards. However, provisions of the Clean Air Act Amendments of 1990 prohibit new emissions standards for heavy-duty trucks from becoming effective until 2004.

California alone among states possesses the independent authority to adopt separate emissions standards for heavy-duty trucks, though other states may choose to implement either federal or California standards. For example, the 1994 California State Implementation included a provision for the California Air Resources Board to adopt lower heavy-duty truck emission standards effective in 2002, two years prior to the changes in anticipated federal standards. Trucking industry spokespersons argue that for California to adopt earlier, tighter standards will place California trucking operators at a competitive disadvantage with respect to truck operators from other states, since more advanced standards may mean more costly vehicles.

New National Emissions Standards for Heavy-Duty Trucks

In 1994, U.S. EPA moved to consider adoption of tighter national truck standards. EPA's published proposal would tighten the 1998 NOx standard of 4.0 g/bhp-hr, by requiring a combined HC+NOx standard of 2.4 g/bhp-hr in 2004. EPA says this is expected to be an effective 2 g NOx standard. PM10 standards would remain unchanged at .01 g/bhp-hr, as would CO and evaporative HC standards. "Useful life" standards would be raised from the

current 290,000 miles to 435,000 miles, seeking to assure greater durability of the emissions performance of trucks built after 2004.

The proposed new national emission standards are expected to be able to be met by manufacturers using more advanced diesel technologies.

Many environmentalists argue that if U.S. EPA adopts the new standards as proposed, it will not be taking advantage of the superior emissions performance opportunity presented by some commercially available alternative fuel trucks. Proponents of alternative fuels worry that heavy-duty engine manufacturers will be less inclined to design and produce more advanced models of alternative fuel engines, if national standards can be met with diesel engine technologies.

Others argue, however, that the diesel engines designed to meet the 2004 standard may not work as well as current diesel engines in important respects and may prove equally costly as alternative fuel technologies. The result may be that current competitive advantages of diesel technology may be somewhat obviated, and an opening will yet be created for alternative fuels, especially if diesel fuel prices continue to rise.

Some environmentalists say that other aspects of the new federal rule, such as the specific formulation of the provisions for averaging, banking and trading, could be very significant in encouraging the development, purchase and use of more advanced, cleaner alternative fuel heavy-duty vehicles. The precise formulation of these rules is one of the matters still being debated. If these rules are aggressive it could help the *ICTC* considerably by giving strong incentives to engine manufacturers to build and aggressively market cleaner alternative fuel heavy-duty engines.

Deregulation and the ICTC

For the purpose of advancing the *ICTC*, national deregulation of the trucking industry has important implications. The ability of individual states to tailor regulations on relevant aspects of trucking operations to encourage the use of alternative fuels has been significantly undermined. For example, national deregulation will make California-only emissions standards very difficult to enforce. In a deregulated environment, truck operators will much more easily be able to choose which states in which to base plate their trucks. If California adopted more advanced emissions standards on new trucks, some operators may choose to base-plate in another state, without changing the actual day to day operations of its trucks, simply to avoid requirements for more costly cleaner trucks.

National Fuel Tax Policy

A recent IRS ruling elected to treat LNG as a "special motor fuel" and to tax it at the same rate as other "special motor fuels. This rate is much higher than the rate at which CNG is taxed. When the energy content of competing fuels is accounted for, LNG is now being taxed at a higher rate than diesel fuel, despite its air quality advantages.

Other alternative fuels are also taxed at a higher rate than diesel fuel on diesel equivalent gallon basis. For example, LPG is also taxed as "special motor fuels" at an effective rate of 27.4 cents and methanol at an effective rate of 27.6 cents per diesel equivalent gallon.

The 1992 Federal Highway Reauthorization Act

The Federal Highway Reauthorization Act prohibited any state from adopting increases in permitted truck length and weight. States permitting "triples" at that time were "grandfathered," but other states are preempted from adopting new regulations in the future which allow triples. This provision in the legislation was the product of a determined and intensive lobbying effort by both the railroad industry and by CRASH, a highway safety advocacy group. Reauthorization up again in 1997. Truckers are somewhat divided on the issue. Small operators, who are unlikely to take advantage of "triples," see it as giving a competitive advantage to larger operators.

Differences in Permitted Truck Length & Weight by State

	California	Nevada	Utah	Arizona
Length				
semitrailer	53'0"	48'0"	53'0"	57'6"
full trailer	28'6"	28'6"	48'0"	28'6"
double	not specified	70'0"	not specified	not specified
triples	not permitted	Allowed with permit except on certain routes. Max. length = 101' Max. weight = 129,000 lb	Allowed with permit on interstate hwy's, I-15 and I-80. Max. length = 105' Max. weight = 129,000 lbs.	Allowed with permit on I-15 and other specified but limited routes
Weight/lbs				
single	20,000	20,000	20,000	20,000
tandem	34,000	34,000	34,000	34,000
gvwr	80,000	80,000	80,000	80,000

As interstate trucks must adopt the weight and length allowances of the most stringent state, it may be advantageous if all states have uniform length standards which favor alternative fuel vehicles.

Safety Regulations

Apart from requirements for safety inspections, most safety related regulations are adopted on a state by state basis. These regulations need to be individually examined to understand if they create barriers to the use of alternative fuel trucks.

2. State Level Regulatory Environment

Differential in State Excise and Sales Taxes

A great deal of variation in state level taxes means that no clear signals are sent to the alternative fuel marketplace.

Air Quality Regulations

Only California possesses the independent authority to develop statewide emissions standards. Other states may choose to adopt California standards or to simply live with the national standards. The California Air Resources Board has adopted a measure in its 1994 State Implementation Plan calling for a 2.0 g/bhp-hr NOx standard for new heavy-duty trucks in California beginning in 2002, two years ahead of the proposed new national standards.

The California trucking industry complains bitterly that the proposed California emissions standard, if it can be enforced, will create a competitive disadvantage for California truck operators. Some say that such a rule is inconsequential because it cannot be effectively enforced: California truck operators will simply base-plate in other states to avoid California jurisdiction.

In any event, the proposed California standard is probably intended principally to keep pressure on U.S. EPA and on the trucking industry to move ahead with revised national standards. It is not clear that it will have much meaning for the ICTC at all, except to the extent that it encourages more aggressive averaging, banking, and trading regulations that encourage manufacturers to build and aggressively market alternative fuel trucks.

To reduce diesel emissions, the California Air Resources Board has adopted specific rules governing the formulation of diesel fuel sold in California. Trucking industry spokespersons say that this rule has several "perverse" consequences: 1) diesel fuel prices go up to cover added refinery costs; 2) California diesel fuel prices go up because the supply of fuel comes from only a few California sources; 3) interstate truckers purchase their fuel in other states where, allegedly, prices are lower, thus subverting the clean air objectives; 4) California truckers are at a competitive disadvantage with non-California truckers.

One effect of the "CARB diesel" rule, along with rising diesel prices in general, will be in an improved competitive price position for alternative fuels vis-à-vis diesel fuel in California. This could encourage some truck operators to consider using alternative fuels.

Regulations which have been adopted by the regional Air Quality Management Districts in California are unlikely to effect trucks engaged in interstate line haul trucking on any of the ICTC routes.

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Site Selection Screen

For more information on a particular site, point and click to check the appropriate box and then press select.

Select Fuel	Station Name	City	State	
☐	LNG Maryland Dept of Transportation	Baltimore	MD	MapIt!
☐	LNG Phoenix Public Transit Department	Phoenix	AZ	MapIt!
☐	LNG Central Contra Costa Transit Autho	Concord	CA	MapIt!
☐	LNG California Trucking Association	Sacramento	CA	MapIt!
☐	LNG BNSF Vernon, CA	Vernon	CA	MapIt!
☐	LNG Southern California Regional Rail	Los Angeles	CA	MapIt!
☐	LNG Overnite-LA	Los Angeles	CA	MapIt!
☐	LNG Conway	Los Angeles	CA	MapIt!
☐	LNG Unocal	Los Angeles	CA	MapIt!
☐	LNG Walmart	Porterville	CA	MapIt!
☐	LNG Viking/ATA Foundation	Sacramento	CA	MapIt!
☐	LNG Cummins West	San Leandro	CA	MapIt!
☐	LNG L.A. County Sanitation District	Whittier	CA	MapIt!
☐	LNG MVE Cryogenics Atlanta LNG Station	Atlanta	GA	MapIt!
☐	LNG Waste Management of Atlanta	Atlanta	GA	MapIt!
☐	LNG BFI Atlanta LNG Station	Atlanta	GA	MapIt!
☐	LNG Idaho National Engineering Laborat	Idaho Falls	ID	MapIt!
☐	LNG Gary Public Transportation Corp.	Gary	IN	MapIt!
☐	LNG Maryland Mass Transit Administrati	Baltimore	MD	MapIt!
☐	LNG BG&E/MDE	Baltimore	MD	MapIt!
☐	LNG Gordon Foods	Brighton	MI	MapIt!
☐	LNG Burlington Northern Railroad	Glendive	MT	MapIt!
☐	LNG EHM LLC-Natural Gas	Bloomfield	NM	MapIt!
☐	LNG Roadway Express	Copley	OH	MapIt!
☐	LNG Northwest Natural Gas	Portland	OR	MapIt!
☐	LNG Chambers-USA Waste LNG Station	Washington	PA	MapIt!
☐	LNG Greater Austin Transportation Comp	Austin	TX	MapIt!
☐	LNG Dallas Area Rapid Transit	Dallas	TX	MapIt!
☐	LNG Sun Metro	El Paso	TX	MapIt!
☐	LNG American Airlines /DFW's LNG Stati	Ft. Worth	TX	MapIt!

☐	LNG Houston Independent School Distric	Houston	TX	MapIt!
☐	LNG United Parcel Service	Houston	TX	MapIt!
☐	LNG Houston Metro	Houston	TX	MapIt!
☐	LNG Katy Independent School District	Katy	TX	MapIt!
☐	LNG H.W. Butt Grocery Company	San Antonio	TX	MapIt!
☐	LNG Praxair LNG's	Willis	TX	MapIt!
☐	LNG Jack B. Kelley	Woods Cross	UT	MapIt!
☐	LNG Virginia Natural Gas	Norfolk	VA	MapIt!
☐	LNG Tidewater/VNG Elisabeth River	Elisabeth	VA	MapIt!
☐	LNG Overnite Transportation Company	Richmond	VA	MapIt!
☐	LNG Paccar Technical Center	Mount Vernon	WA	MapIt!
☐	LNG Detroit Diesel Corporation	Detroit	MI	MapIt!
☐	LNG Cryenco Inc	Denver	CO	MapIt!
☐	LNG LAX Airport	Los Angeles	CA	MapIt!
☐	LNG Amoco	Evanston	WY	MapIt!
☐	LNG Neptune Leasing's San Manuel	San Manuel	AZ	MapIt!
☐	LNG Mesa Pacific LNG's Los Angeles Sta	Los Angeles	CA	MapIt!
☐	LNG Gulf States Airgas	Theodore	AL	MapIt!
☐	LNG ALT-USA's Ontario, CA	Ontario	CA	MapIt!
☐	LNG PCI Clean Fuels Oakland Interim LN	Oakland	CA	MapIt!
☐	LNG Raley's Supermarkets'	Sacramento	CA	MapIt!
☐	LNG UP's City of Commerce II	Commerce	CA	MapIt!
☐	LNG ALT-USA	Denver	CO	MapIt!
☐	LNG BNSF Staples, LNG Station	Staples	MN	MapIt!
☐	LNG Houston Metro's Kashmere No.2	Houston	TX	MapIt!
☐	LNG Houston Metro's Kashmere No.1	Houston	TX	MapIt!
☐	LNG Houston Metro's West LNG Station	Houston	TX	MapIt!
☐	LNG Williams Field Services	Durango	CO	MapIt!
☐	LNG Amoco	Houston	TX	MapIt!
☐	LNG Praxair LNG (NIPSCO)	LaPorte	IN	MapIt!
☐	LNG Praxair LNG (Quadren)	Robbins	CA	MapIt!
☐	LNG ECOGAS	Austin	TX	MapIt!
☐	LNG Mesa Pacific	Satanta	KS	MapIt!
☐	LNG Exxon	Green River	WY	MapIt!
☐	LNG Trussville Utilities LNG Plant	Trussville	AL	MapIt!
☐	LNG GreenFuels, Inc.	Gary	IN	MapIt!

Commercial Applications for Carbon Dioxide

- Food applications: chill meats, vegetables and other food stuffs
- Dry ice applications
- Truck and Rail Car refrigeration applications
- Manufacture of calcium carbonate used in the paper industry
- Waste water treatment applications requiring pH adjustment
- Steel industry: ladle purging
- Cleaning and purging pipelines and oil wells
- Cleaning systems using CO₂ dry ice propelled by compressed air
- Miscellaneous industries such as blow molding applications to reduce cooling times
- Inerting agents injected into foodstuffs to prevent insects invasion
- Fire fighting agent
- Shielding gas in welding applications
- Freeze branding of cattle
- Leak detection