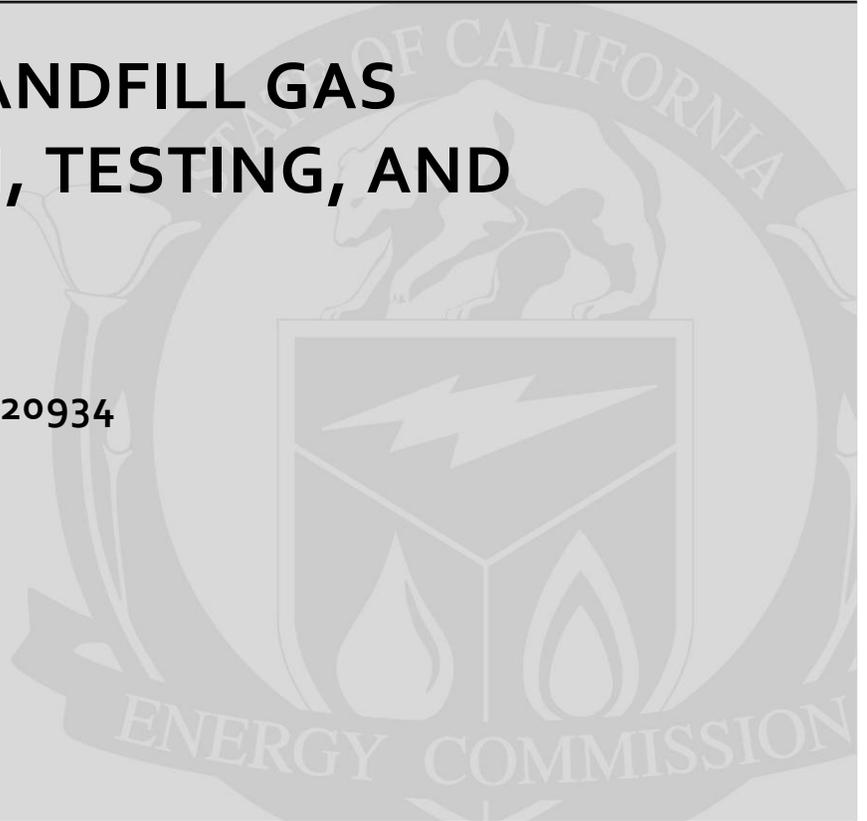


Energy Research and Development Division
FINAL PROJECT REPORT

**ALTAMONT LANDFILL GAS
PURIFICATION, TESTING, AND
MONITORING**

GTI PROJECT NUMBER 20934



Prepared for: California Energy Commission

Prepared by: Gas Technology Institute



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PREFACE

The California Energy Commission Energy Research and Development Division supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

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Altamont Landfill Gas Purification, Testing, and Monitoring is the final report for the Purification and Liquefaction of Biomethane Landfill Gas for Transportation Fuel project (contract number 500-09-004 conducted by Gas Technology Institute. The information from this project contributes to Energy Research and Development Division's Transportation Program.

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ABSTRACT

This Final Report details the activities that were performed to successfully complete the California Energy Commission contract 500-09-004. These tasks included installing equipment and performing checks of the design prior to start-up for the new, advance clean-up system at the Liquefied Natural Gas (LNG) production facility at the Waste Management, Inc., Altamont Landfill in Livermore, California. This project was successfully implemented by a partnership between Gas Technology Institute (GTI) and High Mountain Fuels, a joint venture between Waste Management, Inc. and Linde BOC.

This research program developed and tested an advanced, cost effective, and environmentally friendly technology for the production of transportation biofuel energy for Waste Management, Inc. waste haulers state-wide, beginning in Northern California. Researchers developed critical components in the gas clean-up and liquefaction systems that were demonstrated through the producing transportation quality LNG from landfill gas at the Altamont Landfill and Resource Recovery Facility in Livermore, California. The project results have overcome the technological challenges of landfill gas purification and demonstrate liquefaction technology, using a GTI-patented and High Mountain Fuels developed multi-refrigerant process, to recover and convert renewable landfill biomethane to LNG as a transportation fuel.

Not only is this facility reducing greenhouse gases, lowering NO_x and particulate emissions, and reducing the state's reliance on imported oil products, it also serves as a model for similar facilities in California to use indigenous biogas resources and displace non-renewable fossil fuels.

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EXECUTIVE SUMMARY

Landfills naturally generate methane and other organic compounds as the waste materials in them decompose. This methane is a greenhouse gas (GHG), and contributes to global warming if left to vent to the atmosphere. Methane is also the primary component of natural gas. The Liquefied Natural Gas (LNG) production facility at the Altamont Landfill can refine landfill gas that conforms to accepted natural gas quality standards, and use it in natural gas applications. One important such application is the fueling motor vehicles. California promotes developing practical renewable alternative fuel vehicle technologies that reduce emissions and reliance on foreign petroleum imports. Pipeline supplied natural gas (methane) has proved to be a viable, alternative fuel in certain applications, and purified landfill gas will provide a domestic, renewable, local source of biomethane to fuel natural gas vehicles.

There are significant renewable biomethane resources generated within California at wastewater treatment plants, landfills, and dairy and swine farms. Those potential energy resources are either a detriment to the environment (i.e., the gases are vented or flared) or are used positively to generate electricity or heat. The Altamont facility expands a new value-added LNG product as a transportation fuel. Between 2005 and 2020, total methane generation for conventional landfill in California, assuming no change in the current per capita waste disposal rate, is estimated to increase from 80 to 110 billion cubic feet per year (bcf/y) however, if bioreactor landfills are widely used, the potential for biomethane production can increase to 145 bcf/y by 2020¹. Currently, this resource is supplemented by biomethane using anaerobic digestion produced from wastewater treatment plants and agricultural sources, secondary markets for this liquefaction technology. Applying conservative assumptions of 80 bcf/y of biomethane, this could displace more than 550 million gallons of diesel fuel a year if used only as a vehicle fuel.

Recognizing there are currently other value-added uses of biomethane, if only 10 percent is used for vehicles (about 8 bcf/y), it could offset California's demand for imported diesel fuel by more than 55 million gallons per year and avoid fossil fuel CO₂ emissions of 1.1 million pounds annually. Additionally, lower NO_x and particulate emissions from using more low-emission LNG-powered heavy duty vehicles will be realized, supporting California's air pollution reduction goals. Furthermore, since the facility captures gas that is currently being flared, and uses it in the transportation sector, additional energy security and air quality benefits are reached by displacing conventional diesel fuel supplies. In this instance, using a renewable fuel improves air quality, and addresses the state's goal of transitioning to a transportation system based on alternative fuels such as LNG.

High Mountain Fuels (HMF) leads the commercialization effort. HMF is a joint venture between Waste Management, Inc. (WMI), the largest landfill owner/operator and a large consumer of LNG in refuse trucks in the United States, and Linde BOC (Linde), the largest supplier of

¹ Williams, Robert B., Jenkins, B.M, Kaffka, Steve (California Biomass Collaborative Department of Biological and Agricultural Engineering). 2008. An Assessment of Biomass Resources in California, 2007, 2010 and 2020. California Energy Commission. Publication Number: CEC-2013-052.

cryogenic gas products in the world. HMF is supported by Gas Technology Institute (GTI), a leading natural gas research and development organization whose mission is focused on the developing and introducing new energy technologies.

The LNG production facility at the WMI Altamont Landfill and Resource Recovery Facility in Livermore, California can consume more than 2,600 standard cubic feet per minute (scfm) of collected landfill gas. The project's primary technical goals were for the facility to remove contaminants and purify the methane before liquefying it by cooling to cryogenic temperatures using a GTI-patented multi-refrigerant process. The LNG product meets stringent transportation grade fuel specifications before being supplied to the WMI fleet and other consumers. The facility has an operational capacity of 13,000 LNG gallons per day (gpd) which will displace more than 2.8 million gallons per year of diesel fuel. The LNG production facility is considered GHG neutral since the methane that is currently flared at the landfill (resulting in CO₂ emissions) will be liquefied to LNG, then combusted in vehicles, resulting in the equivalent CO₂ emissions. There are significant GHG emission reductions when the vehicles fueled by the LNG are compared to similar diesel fueled vehicles. These LNG vehicles will reduce GHG emissions by an amount equal to the displaced diesel fuel emissions. Production is projected at more than 2 million gallons of diesel per year and will reduce 31,800 tons per year of CO₂ emissions.²

LNG Production Facility Goals

GTI and their partners constructed an LNG production facility that could consume approximately 2,600 scfm of collected landfill gas and produce 13,000 gpd of LNG. The LNG plant at the Altamont Landfill facility meets or exceeds the performance specifications when running at full capacity since the plant is currently stable in producing up to 14,000 gpd. This project displaces diesel use, reduces GHG emissions, lowers NO_x and particulate emissions, and reduces the state's reliance on imported oil products, and also serves as a model for similar facilities in California to use indigenous biogas resources and displace non-renewable fossil fuels.

Onsite electricity generation, using additional methane, meets all power requirements for the system (gas and refrigeration compressors, controls, transfer pumps, auxiliaries, etc.). The final LNG product is stored on-site in an insulated cryogenic tank until it is trucked by a 10,000 gallon capacity tanker truck to existing LNG dispensing locations in California.

The technical goals of this Energy Commission project's tasks were:

- Verify the suitability of the demonstration site and take delivery of the necessary equipment and supplies to operate the LNG production facility
- Install the equipment, controls, and support infrastructure according to the system design specifications
- Start-up the system and equipment on-site and commission the system into operation

² EIA website for emission coefficients, <http://www.eia.doe.gov/oiaf/1605/factors.html> diesel: 22.384 pounds of CO₂ emissions per gallon of Diesel fuel

- Test critical components in the gas clean-up and liquefaction systems and demonstrate the production of transportation quality LNG

CHAPTER 1:

Background and Objectives

This project developed advanced transportation technologies to reduce air pollution and GHG emissions beyond applicable standards and benefit electricity and natural gas rate payers (Public Resources Code Section 25620.1.(b)(1)), (Chapter 512, Statutes of 2006). The project supports California's goal to research, develop, and demonstrate alternative fuel production technologies, emphasizing in-state resources as discussed in *2005 the Integrated Energy Policy Report*.

Purifying biogas, the most challenging is landfill gas, is a complex process and many variables can have a significant effect on the design and trade-offs. These variables include:

- a) Individual impurities
- b) Combination of impurities
- c) Concentration of each gas component / impurity
- d) Variations in gas concentrations / impurities

It is critical that the technology selection and process design is both effective and reliable and in line with the business case requirements regarding capital and operating costs, plant availability, and methane recovery and product specifications.

This research program developed and tested an advanced, cost effective, and environmentally friendly technology to produce transportation biofuel energy for WMI waste haulers state-wide, beginning in Northern California. Researchers will develop critical components in the gas clean-up and liquefaction systems that will be demonstrated through the production of transportation quality LNG from landfill gas at the Altamont Landfill and Resource Recovery Facility in Livermore, California. The results of this project will overcome the technological challenges of landfill gas purification and demonstrate liquefaction technology for the recovery and conversion of renewable landfill biomethane to LNG as a transportation fuel.

CHAPTER 2:

Description of the PSA Process

2.1 Pressure Swing Adsorption

Adsorbents are widely used for gas purification through the Pressure Swing Adsorption (PSA) process. The adsorbent pores provide the surface for gas or liquid molecules to collect (adsorb), and thus be separated from the incoming stream. Once the adsorbent is *saturated* with the adsorbed species, it can be regenerated by rejecting the previously adsorbed species. Regeneration is accomplished by lowering pressure and raising temperature or purging the adsorbent. Thus, the adsorbent can be used over and over again.

In the PSA process, the targeted species is removed at high pressure and adsorbed at low pressure – hence the “pressure swing”. Since pressures can be rapidly changed, cycle times are short and the process is robust with the main moving parts in the PSA unit being the on/off valves. Many thousands of systems, many of which are larger than 100 million standard cubic feet per day (MM SCFD) of feed, are in operation for gas separation though relatively few are used in the natural gas industry. The reason for the limited applications for natural gas is the high methane adsorption of traditional adsorbents.

Landfill gas contains a wide range of impurities including water vapor, volatile organic compounds (VOCs), siloxanes, hydrogen sulfide (H₂S), CO₂, and other contaminants (collectively the “impurities”) that must be removed to produce gas suitable for use as pipeline gas in the production of LNG or compressed natural gas (CNG). In upgrading landfill gas, the Guild Molecular Gate™ process uses adsorbents that are targeted to remove the heavy impurities while removing CO₂ to a typical 1-2% level. In a base design nitrogen and oxygen are not removed and pass into the product with the product CH₄; thus product gas in a base design contains 1-2% CO₂ as well as CH₄, N₂, and O₂ (collectively the “lights”). Where N₂ and O₂ require removal, a second stage PSA unit is typically used for removal of these impurities.

2.2 PSA Process Used

The operating principal behind the process is PSA. PSA is based on the principle that an adsorbent will load a higher amount of a target molecule at higher pressures and release the molecule at low pressures. This principle is applied in a cyclic process and includes the following steps:

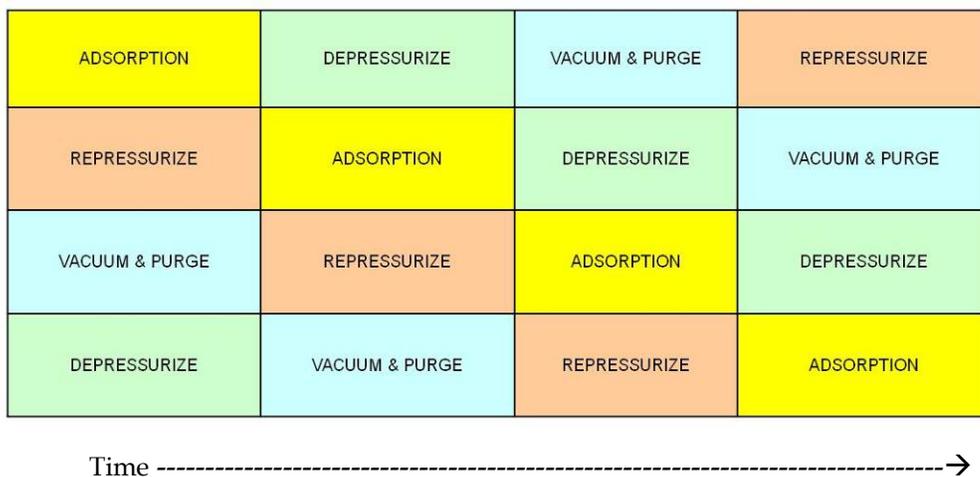
1. Adsorption – Feed gas containing the “impurities” and the “lights” is fed to the adsorber vessel at high pressure. The impurities are adsorbed on the adsorbent, and the lights pass through the bed as the product gas. This step is continued until the adsorbent is saturated with the impurities.
2. Equalization (down in pressure) – At the conclusion of the adsorption step, the adsorbent contains high levels of impurities but the voids in the bed contain feed gas. To prevent wasting the void gas (mostly CH₄), the high pressure is used to transfer this

gas to other lower pressure vessels. An *equalization* is performed, whereby the high and low-pressure vessels are allowed to equalize to a common intermediate pressure. There are usually one to four equalizations, with the optimum dependent on many factors that are integrated into a model. The bed can be equalized with another bed (heading up in pressure) or to a tank. Equalizations that are downward in pressure are done concurrently, in the same direction as the adsorption step.

3. Blowdown/Purge – The previous steps are engineered to separate the void gas from the adsorbent bed and leave the impurities inside the vessel. At this point, the adsorbent and voids are rich in impurities. The impurities are removed (and the adsorbent regenerated) by *blowing down* the vessel in a counter-current direction to low pressure. The vessel is then swept, or *purged*, with gas to remove most of the adsorbed impurities. Purge can take place at pressures above atmospheric or through the use of a vacuum pump under vacuum. Vacuum is typically used in landfill gas service.
4. Equalization (up in pressure) – Once regenerated, the adsorbent bed is clean and basically filled with CH₄ at low pressure. Before it can be put back in service to repeat the removal of the impurities it must be increased in pressure. This is done by receiving equalizations gas from another vessel or tank (from step 2 above).
5. Re-pressurization – Equalizations are not sufficient to fully repressurize the bed. To more fully repressurize the bed some product gas is typically used (feed can be used) to complete the repressurization.
6. Adsorption – The bed begins the cycle again.

In a simplified form the process steps are illustrated in the figure below. The cycle chart shows a basic four vessel cycle wherein one vessel is on adsorption at any point in time, one vessel depressurizes, one vessel blows down/purges, and one vessel repressurizes.

Figure 1: PSA Process Cycle Chart



CHAPTER 3: Technical Tasks

The following is a summary of the technical tasks that were performed under this project. More detailed descriptions and technical information is contained in the Critical Project Review Reports as well as the project deliverables, as described below.

3.1 Task 2.0 – Demonstration Site and Design Analysis and Equipment, Materials and Supplies Delivery

The goal of Task 2.0 of this grant is to verify the suitability of the demonstration site and take delivery of the necessary equipment and supplies to operate the LNG production facility. Major equipment components were designed to be fabricated on skids and then shipped for on-site assembly. Determination of necessary equipment and supplies are dependent upon compilation and consolidation of data, designs, and reports summarizing the preliminary project work.

3.1.1 Task 2.1 – Site Design and Gas Analysis

Liquefaction of pipeline quality natural gas on a large scale is commonplace around the world; however small-scale operations (5,000 to 50,000 gpd) have presented technological and economic challenges. In recent years, there have been fledgling attempts of small-scale production of LNG from landfill gas. For various reasons, these efforts to date have not proven very successful. This situation is due to several factors, including the attempted use of systems that purify contaminants in a single step, an apparent lack of sufficient laboratory testing, and the inability of smaller and under-financed companies to adequately address the technical and market needs that have arisen during initial deployment.

More details are provided in the Site Design and Gas Analysis Report (Appendix A of the first CPR Report).

3.1.2 Task 2.2 – Gas Clean-up System Research and Design

The clean-up system technology processes raw landfill gas by removing unwanted components such as carbon dioxide (CO₂), nitrogen (N₂), hydrogen sulfide (H₂S), moisture, and reactive organic compounds. The resulting gas is liquefied into a cryogenic fluid at an average temperature of approximately -260° F.

The clean-up process uses a multi-stage approach which was designed to target the removal of chemical families of compounds. The risks involved with using a new technology were mitigated through extensive testing at a landfill site and by incorporating well-known unit operations, employing selective adsorbent and chilling combinations, into the purification system. All unit operations utilized in this system are also conventional and proven.

More details are provided in the Gas Clean-Up System Research and Design Report (Appendix B of the first CPR Report).

3.1.3 Task 2.3 – Liquefier, Storage, Dispensing Equipment Sizing and Design

The liquefier design, based on the GTI-developed and patented small-scale technology, focused on low capital cost and power efficiency. A five-component mixed refrigerant design was selected because of its inherent high efficiency. The liquefier is more efficient than a standard nitrogen cycle system and offers superior specific power as compared to other small-scale technologies. A patented process control system is used to regulate a key warm-end refrigerant component (i-C5) level in the refrigerant mixture. Hence, the cooling curve can be adjusted in real time to optimize power consumption as ambient conditions change resulting in even lower power cost. To reduce capital cost and facilitate the design of standardized systems, the refrigerant loop consists of proven, reliable and low cost components typically used in the Heating Ventilation and Air Conditioning (HVAC) industry.

More details are provided in the Liquefier, Storage, Dispensing Equipment Sizing and Design Report (Appendix C of the first CPR Report).

3.1.4 Task 2.4 – Gas Integrated Systems Engineering

The three main sub systems (landfill gas clean-up, methane liquefaction and trailer loading) were combined and engineered into one seamless system. A control system was developed so that operators have a seamless view of the entire system and can adjust parameters anywhere in the plant. HMF hired an engineering firm to assure all aspects of the integration were documented and issued construction drawings developed.

More details are provided in the System Design Report (Appendix D of the first CPR Report).

3.1.5 Task 2.5 – Site Work and Construction

The site work and construction activities were performed in accordance with the design specifications from the tasks above, in preparation for the arrival of the equipment to the site. Site grading and site mobilization were completed then the Mechanical and Electrical site work contracts were awarded to be followed by the framing and pouring of the site foundations.

More details are provided in the Site Construction Report (Appendix E of the first CPR Report).

3.1.6 Task 2.6 – Equipment and Supplies Tracking and Inventory

The majority of the equipment was assembled in shops on skids that were piped, wired and tested prior to shipping and delivery to the project site. A list of the skids installed and pictures of the equipment delivery are included in the Bill of Materials Inventory List (Appendix F of the first CPR Report).

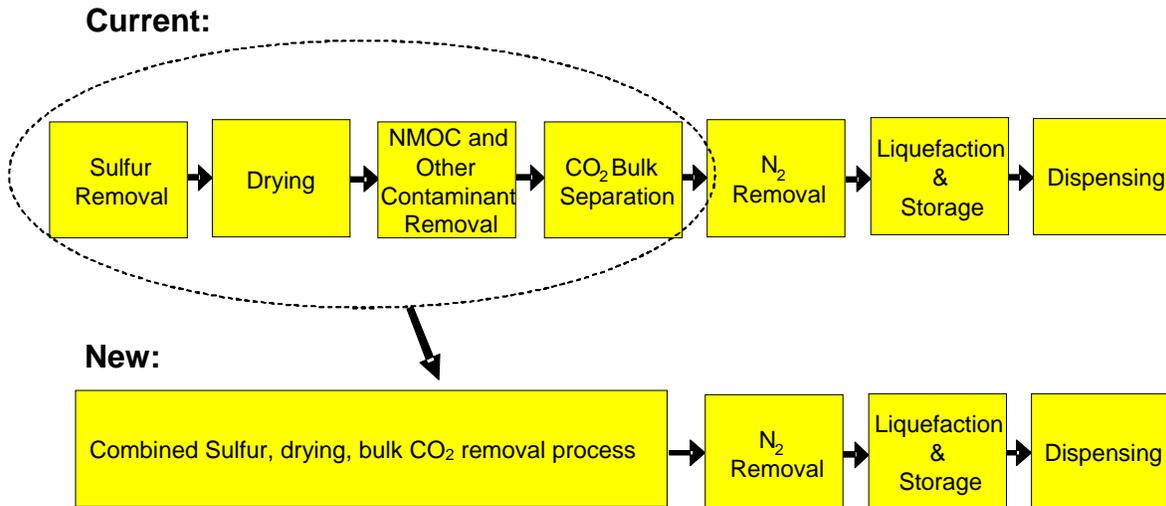
3.2 Task 3.0 – Equipment Installation

A biogas PSA clean-up system was designed and tested for removal of landfill gas contaminants such as sulfur compounds, water, siloxanes, halogens and other hydrocarbons, CO₂, and N₂ to produce feed gas for a Linde developed mixed hydrocarbon refrigerant liquefier system.

The current Altamont Landfill Gas to LNG system is a multistage process with each stage decreasing impurities and increasing the methane (CH₄) content to level suitable for liquefaction and transport to storage and later use as vehicle fuel.

Presently various media are used to remove sulfurs, non-methane hydrocarbons, and volatile organic compounds (VOC) at different stages in the process. Other stages along the current process decrease the presence of CO₂ and nitrogen (N₂) to enrich the CH₄ content.

Figure 2: Landfill Gas Clean-up Process Comparison



The new process, as shown in the figure above, simplifies the current process by combining trace impurities and CO₂ removal into a single stage. A single bed test apparatus was tied into the landfill gas feed after compression and the waste and product streams were connected to the flare header. All three streams were analyzed for bulk and trace components.

3.2.1 Gas Analysis

Trace impurities were measured using an Ion Molecular Impact Mass Spectrometer, also known as Soft Ionization Mass Spectrometry. The analyzer continuously scans the sample; ionization is achieved using one of three source ion gases to impart sufficient energy to remove an electron leaving the molecule intact. Ionization levels are determined by selecting one of three source gases that limit the achievable ionization level.

The model used was a V&F AirSense which reflects the latest development step within the series of our analyzers based on the technology of Ion-Molecule Reaction mass spectrometry (IMR-MS). This analyzer is the multi-purpose level model focusing applications for non-limited gas components, highest flexibility and robustness all in one.

Major components above 100ppm were detected using a Siemens Maxum II Gas Chromatograph TCD set up for Natural Gas analysis, C1 to C6+, O₂, N₂, and CO₂. The application is an industry standard technique using 1/8" packed column technology to better handle any process upsets. Analysis time is approximately 4 minutes per cycle for three channels; each channel is optimized for a segment of the total analysis.

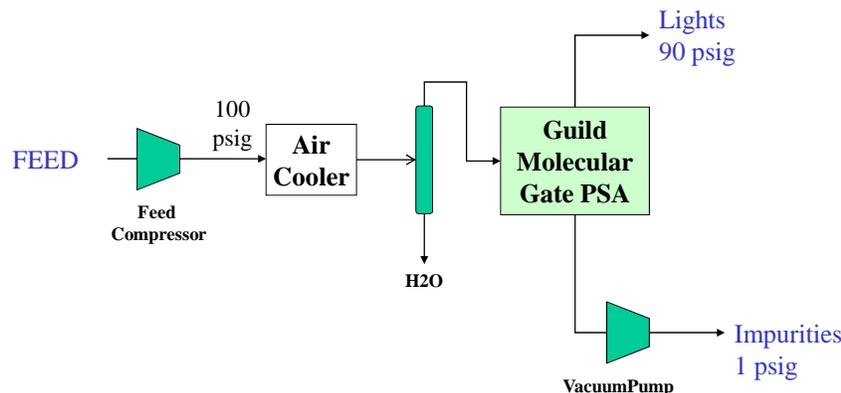
More details are provided in the Installation Report (Appendix A of the second CPR Report) and the Gas Clean-up System Testing and Monitoring Plan (Appendix D of the second CPR Report).

3.3 Task 4.0 – System Start-up and Commissioning into Service

For the field studies, an approach was taken where one adsorber vessel and a series of buffer tanks were used. The operation of the unit used for the field studies uses the same adsorbents and follows the same steps as a commercial system but does so using one adsorber vessel and a series of buffer tanks. The process operates as follows:

1. Feed gas is compressed from the landfill at near atmospheric pressure to approximately 100 psig.
2. A measured and controlled amount of compressed feed gas is fed to the adsorber vessel. Impurities are adsorbed and the product gas lights flow through the bed as product. The product gas is measured for impurities.
3. Feed gas is terminated.
4. The adsorber vessel is depressurized into a series of buffer tanks until a desired pressure is reached.
5. The vessel blowdown through a vacuum pump and the gas desorbed flows through a tail gas buffer tank (as part of the “Tail Gas”).
6. A controlled amount of purge gas is swept through the vessel under vacuum and the adsorber bed is swept of impurities. From the vacuum pump the gas is sent to the tail gas buffer tank.
7. The now cleaned adsorber vessel is repressurized back to ~100 psig using gas from the buffer tanks in step #4 above.
8. The cycle repeats.

Figure 3: PSA Operation Process Diagram



3.3.1 Cycle Optimization

The adsorption step is volume limited on impurities to be removed. This means that each adsorber vessel has the capacity to treat a fixed quantity of gas, for a given impurity

concentration and pressure. Therefore, to minimize adsorbent inventory and vessel size, rapid cycles are preferred. Cycle times are limited primarily by gas velocity, which must be kept below the velocity that would cause adsorbent movement.

Increasing the number of equalizations improves recovery (methane yield), but this must be economically balanced against the added adsorbent, vessels, and valves required. Practical ranges are one to four equalizations. Use of a vacuum pump and longer blowdown/purge cycles tend to benefit performance by more thoroughly removing the adsorbed impurities. Again, the optimum is reached by balancing against capital/operating costs for the vacuum pump.

More details are provided in the Start-up Test Plan (Appendix B of the second CPR Report).

3.4 Task 5.0 – Gas Clean-up System Testing, Monitoring, and Analysis

The goal of this task is to test critical components in the gas clean-up and liquefaction systems and demonstrate the production of transportation quality LNG.

The test apparatus was operated for two months prior to trending for major components and trace impurity concentrations. Initial work involved evaluating qualitatively which trace impurities to trend on feed gas and final product analysis.

Major bulk components, CH₄, N₂ and CO₂ were measured to determine the extent of CO₂ removal. Analysis of the feed gas indicated the following components were present at levels significantly above the analyzers background noise level (i.e. detection limit). The selected impurities were trended quantitatively in the final product.

- i. H₂S
- ii. Methyl Mercaptan
- iii. Ethyl Mercaptan/ Dimethyl Sulfide
- iv. Carbonyl sulfide
- v. Ethanol
- vi. Acetone
- vii. Methyl Ethyl Ketone
- viii. Toluene
- ix. Unidentified compound, mass 114,
- x. Unidentified compound, mass 127, possible chlorinated compound
- xi. Benzene

D3, D4, L2MM and L3MM siloxanes did not appear in significant amounts in the feed gas and were below detection limit of the analyzer, detection limits estimated in the <0.010 ppm.

Two unidentified compounds were present, at mass 114 and 127. 127 may be chlorinated based on possible Cl 35/37 isotopes. Mass 114 does not seem to have potential isotope masses present reducing the likelihood it is chlorinated.

More details are provided in the second CPR Report and the Gas Clean-up System Testing and Monitoring Plan (Appendix D of the second CPR Report).

CHAPTER 4: Project Testing and Reports

4.1 Overall Site Steady-State Operation Test

The performance test was conducted in two parts. A 24 hour hands-off test was performed that was designed to test the clean-up system at design flow rates and allow for maximum liquid production. A second 10 hour test period was conducted immediately following the 24 hour hands-off test at a point closer to the liquefier design flow rate of 13,000 gpd. This was required due to the intended over design of the clean-up system capacity relative to the liquefier. This was intended to be a 12 hour test, but was limited to 10 hours due to a required flare shut down. Once the plant was stabilized, after the flare shut down, a 12 hour period with no trailer fill was recorded near the 13,000 gpd production rate as a bench mark. That data is included here as well.

During the 24 hour hands-off portion of the test, the clean-up system was set slightly above design clean-up flows and the liquefier was set to liquefy as much product as possible, venting the balance. During this portion of the test, the product flow meter was valved in upstream of the product vent valve, thus measuring all the methane produced by the clean-up system, but not all methane being liquefied. Tank levels were recorded during this portion of the test to determine the liquefier production rate. During this portion of the test the results are as follows:

Table 1: 24 Hour Hands-off Test Results

Avg CH ₄ Flow Rate	53,230 scfh
LNG Produced	15,466 gallons ¹
CH ₄ Content	96.60%

1. Based on tank level increase

After the 24 hour hands-off test the clean-up system flow was reduced to a point where no venting between the clean-up system outlet and liquefier was occurring. Valving was switched to place the product flow meter downstream of the product vent valve, thus measuring all product being liquefied. Clean-up system output was further reduced to achieve close to 13,000 gpd production rate through the liquefier with no venting. The plant was run in this mode for a period of just over 10 hours when a plant shut down was required due to maintenance on the flare. We also had one trailer fill during this period. During this portion of the test the plant produced:

Table 2: 10 Hour Test Results

Avg LNG Production Rate	13,440 gpd
CH ₄ Content	97%

After the flare came up the plant was restarted and again lined out at approximately 13,000 gpd. Several trailer fills were then conducted. We selected a 12 hour period to document steady operation with no trailer fills to avoid any skew in the production data correlation between FI-45-1 and tank levels. During this portion of the test the plant produced:

Table 3: 12 Hour Test Results

Avg LNG Production Rate	13,187 gpd
Actual LNG Produced	6,944 gallons
CH ₄ Content	97%

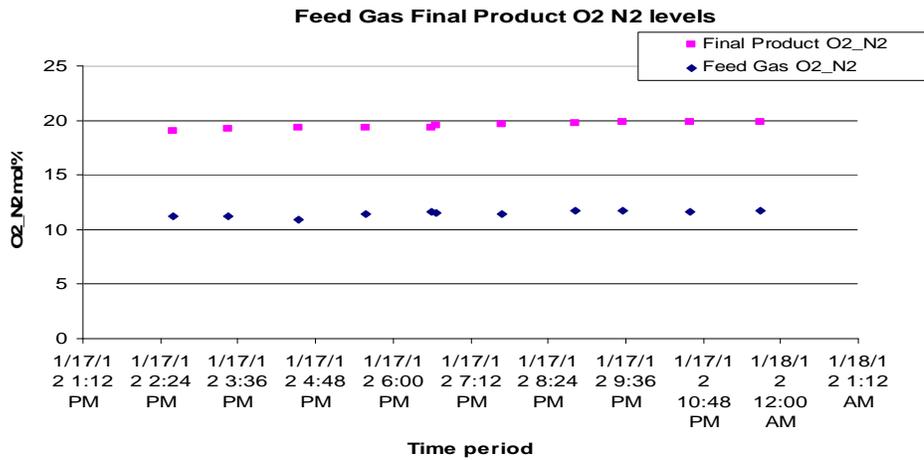
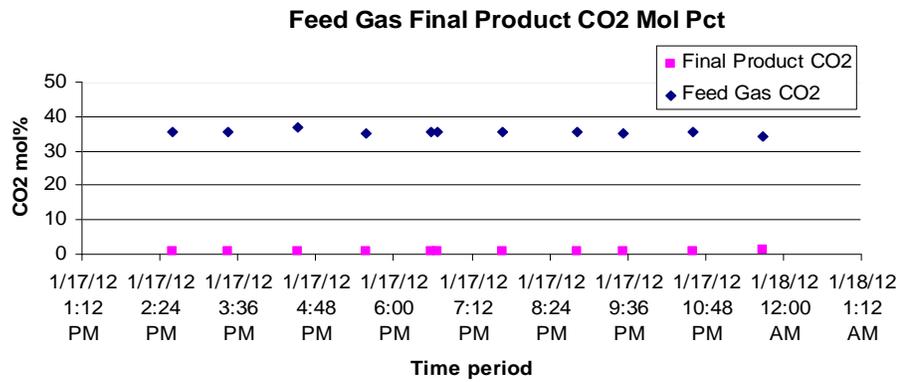
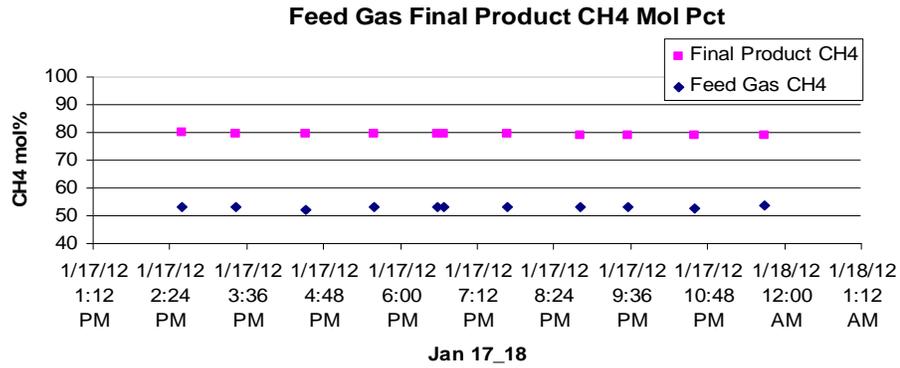
While the plant appears to be capable of producing 15,000 gpd, sustained production at this rate would need to be studied further, taking into account ambient conditions, controller tuning, MR composition etc. The plant is currently very stable in production ranges up to 14,000 gpd.

4.2 Summary of Data Collection for Major Components and Impurities

4.2.1 Summary of Major Component Data Collected

During the period of initial startup feed gas and final product composition was measured. Note that the product at about 80% has as the remaining impurities N₂ and O₂ and CO₂ at a 1-2% level since this the system is not designed to remove N₂ or O₂ and the CO₂ in the product is controlled to the 1-2% level.

Figure 4: Major Gas Components



4.2.2 Summary of Impurities Data Collected

A summary of the impurities detected are shown in the table below.

Table 4: Summary of impurities detected in the feed stream and trended in the final product

Component	Feed Stream	Test Skid Final Product (< shown to represent below detection limit)
Hydrogen Sulfide	25	<0.005
Ethanol	520	<0.030
Methyl Mercaptan	6	<0.005
Acetone	34	<0.030
Dimethyl Sulfide	6	<0.005
Methyl Ethyl Ketone	22	<0.030
Carbon DiSulfide	2	<0.005
Toluene	4	<0.005
mass 114 SIG Hg	0.04	<0.005
Mass 127 SIG Hg	0.07	<0.005
Freon 12	30	<0.005
Carbonyl Sulfide	17	<0.005
Benzene	2.3	<0.005

4.3 Project Reports

The testing performed with the new PSA equipment has been conducted and results are provided in the appendices of the second CPR Report. The appendices include:

- a) Installation Report
- b) Start-up Test Plan
- c) Analyzed and Collected Operation Data
- d) Gas Clean-up System Testing and Monitoring Plan
- e) Testing Results Report

CHAPTER 5: Opportunities Moving Forward

The success of the LNG production facility at the Altamont Landfill is a clear indication of the possibilities for small-scale liquefaction of landfill gas as well as methane-rich gas from anaerobic digestion and traditional natural gas sources. A further indication of the potential for commercial success is that Linde has used this same technology at two additional locations around the world. The first location is in Guilford, England using landfill gas as the feedstock to produce approximately 10,000 gpd of LNG. The second is in Tasmania, Australia which uses a traditional natural gas feedstock to produce over 30,000 gpd of LNG. There are several lessons, described below as well as throughout this report, that have been learned through the construction and operation of these facilities that should be used to evaluate opportunities moving forward.

One of the first factors that is considered is the scale of the facility, i.e. available amount of the gas resources, because it has a dramatic effect on the per gallon cost of LNG production. As scale increases there is a significant increase in efficiency experienced from the higher throughput of product through many fixed-price costs. Another important factor is that the source of the gas is a major driver in the development and costs, both capital and operating costs, of the gas clean-up system. Landfill gas is difficult to purify because it can have varying compositions of major components and impurities as well as varying flow rates where other biogas sources, such as some food processing facilities and agricultural wastes, can be much more consistent. Consistency allows for an optimized system and decreased costs per volume of gas. Additional factors such as the difference in natural gas and diesel pricing, the method of product delivery, availability of incentives, and the product's end use are critical to the development of future opportunities.

There are a number of non-renewable target applications for small-scale (e.g. 5,000 – 30,000 gpd) liquefiers in order to meet rising LNG demand for Class 8 trucks, marine vessels, mining trucks, locomotives, well drilling, pressure pumping, ISO shipping containers, etc. These applications include:

- Monetizing stranded gas wells - - liquefy gas at shut-in gas-producing well-heads (e.g. locations in Pennsylvania, North Dakota and Texas) where gas gathering and pipeline transport is uneconomical or impractical
- Monetizing flare gas and reduce GHG emissions - - liquefy flared gas at predominantly oil producing well-heads (e.g. locations in North Dakota) where gas gathering and pipeline transport is uneconomical or impractical
- Serving new small LNG peak-shaving facilities at remote communities, where natural gas pipeline capacity is limited or the service area is dependent on a single pipeline (by making LNG from pipeline gas)
- Providing LNG on-site at local truck depots, marine bunkering facilities, etc. for transportation fleet operators and others who want to ensure local LNG availability and

have greater cost control while the larger national LNG supply infrastructure builds out (by making LNG from pipeline gas)

- Satisfying LNG demand in markets across U.S. where larger liquefiers are distant or potentially sold-out, by making LNG from pipeline gas as needed (including temporary production until additional larger liquefiers are available)

A concern in the development of small-scale liquefaction is that demand for LNG in North America has expanded so quickly that large LNG liquefaction plants appear to be justifiable in many major markets, so it is desired that small-scale LNG liquefiers compete with larger, higher-efficiency, lower unit-cost plants in these markets. Innovative, lower-cost pre-treatment systems and other developments may help accelerate the installation of small-scale versus large LNG plants. Furthermore, the economics for renewable LNG (R-LNG) are challenging because the price of natural gas has come down so much since 2008. The Henry Hub yearly average for spot natural gas prices in 2008 was \$8.93/MMBTU where the current price is less than \$4/MMBTU.

The availability of Renewable Identification Number (RINs) and carbon credits help to offset ongoing costs of R-LNG production but launching new R-LNG projects is especially challenging because the value of the RINs cannot be counted on when making large capital investment decisions due to their widely fluctuating prices. There is a strong desire from R-LNG developers for the government agencies (e.g. US EPA and/or the US DOE) to help spur more projects by de-risking the RINs and carbon credits. Another issue is the class of RINs that are generated from a facility such as the Altamont Landfill. R-LNG projects generate D-5 RINs, which are the same class as Brazilian sugar cane ethanol, so increased ethanol imports could have a very significant impact on the RIN value. Reclassifying R-LNG RINs into a different category would help maintain future value even though it would not entirely remove the risk of future project valuation. It is also unclear whether the RINs and carbon credits apply for fueling coastal vessels and locomotives however if they do pertain, it would provide an additional market in industries that have fast growing interest in LNG.

In summary, there is a continued interest for small-scale LNG in some specific areas and applications however the North American "fossil" LNG market has expanded so rapidly that larger plants are now justifiable in many markets. It remains to be seen whether small-scale LNG plants can compete with larger, neighboring plants. Continued governmental support in the form of grants, RINs and carbon credits, tax incentives, etc. are critical to the further implementation of R-LNG facilities in order to reduce risks and accelerate the development of innovative, lower-cost technologies.

CHAPTER 6: Conclusions

This project developed advanced transportation technologies that reduce air pollution and GHG emissions beyond applicable standards; benefit electricity and natural gas rate payers (Public Resources Code Section 25620.1.(b)(1)), (Chapter 512, Statutes of 2006); and support California's goal to research, develop, and demonstrate alternative fuel production technologies, emphasizing in-state resources per the Integrated Energy Policy Report 2005. There are very significant renewable biomethane resources generated within California at wastewater treatment plants, landfills, as well as dairy and swine farms. In many cases these potential energy resources are either a detriment to the environment (i.e., vented or flared) or are used positively to generate electricity or heat. This facility expands the opportunities into a new value-added product in the form of LNG as a transportation fuel.

Purification of biogas, the most challenging of which is landfill gas, is a complex process and many variables can have a significant effect on the design and trade-offs. Therefore, it was critical that the technology selection and process design was both effective and reliable as well as in line with the business case requirements with respect to capital and operating costs, plant availability, and methane recovery and product specifications.

In this project, a biogas PSA clean-up system was designed and tested for removal of landfill gas contaminants such as sulfur compounds, water, siloxanes, halogens and other hydrocarbons, CO₂, and N₂ to produce feed gas for a GTI-patented and Linde developed mixed hydrocarbon refrigerant liquefier system.

The current Altamont Landfill Gas to LNG clean-up system is a multistage process with each stage decreasing impurities and increasing the methane (CH₄) content to levels suitable for liquefaction and transport to storage and later use as vehicle fuel. Presently various media are used to remove sulfurs, non-methane hydrocarbons, and volatile organic compounds (VOC) at different stages in the process. Other stages along the current process decrease the presence of CO₂ and nitrogen (N₂) to enrich the CH₄ content. The new process, that was developed and tested in this project, simplifies the current process by combining trace impurities and CO₂ removal into a single stage. A single bed test apparatus was tied into the landfill gas feed after compression and the waste and product streams were connected to the flare header. All three streams were analyzed for bulk and trace components to record the successful removal of all impurities.

This research program developed and tested an advanced, cost effective, and environmentally friendly technology for the production of transportation biofuel energy for WMI waste haulers state-wide, beginning in Northern California. Researchers developed critical components in the gas clean-up and liquefaction systems that were demonstrated through the production of transportation quality LNG from landfill gas at the Altamont Landfill and Resource Recovery Facility in Livermore, California. The results of this project have overcome the technological

challenges of landfill gas purification and demonstrate liquefaction technology for the recovery and conversion of renewable landfill biomethane to LNG as a transportation fuel.

This report signifies the successful completion of Altamont Landfill Gas Purification, Testing, and Monitoring Project under CEC contract 500-09-004.