4.0 REDUCING POTENTIAL FOR CLIMATE EFFECTS OF NON-CO_2 GREENHOUSE GASES

4.1 METHANE EMISSIONS FROM ENERGY AND WASTE

4.1.1 ANAEROBIC AND AEROBIC BIOREACTOR LANDFILLS

Technology Description

Landfill bioreactor cell, Yolo County, California

In recent years, bioreactor landfills have gained recognition as a possible innovation in solid-waste management. The bioreactor landfill is generally defined as a municipal solid-waste landfill, designed and operated in such a manner that liquids are added to the waste mass to accelerate the decomposition of the waste. There are currently two bioreactor processes – anaerobic and aerobic. Hybrids employ both methods. The primary difference between the two is that, in anaerobic bioreactors, a key objective is to enhance the generation of landfill gas (i.e., methane), by minimizing oxygen infiltration, over a shorter period of years; whereas, in aerobic bioreactors, the objective is to minimize landfill gas generation overall by introducing oxygen into the waste mass. Both methods utilize leachate recirculation and/or supplemental liquid non-hazardous waste addition as a means to control and enhance moisture levels within the landfill, thereby increasing decomposition and enhancing landfill gas production.

Current Research, Development, and Demonstration

RD&D Goals

- The first commercial full-scale anaerobic and aerobic bioreactor technology was operational in 2002. The goal is to have three-five commercial full-scale demonstration units operational by the close of 2006.
- Environmental, public-health impacts, and design and operational issues need to be further evaluated.
- Undertake a program of market penetration 2007–2012.

RD&D Challenges

- No long-term, full-scale commercial application demonstrated.
- Environmental, public-health impacts, and design and operational issues need to be addressed.
- A regulatory barrier to the deployment of the bioreactor landfill is the Resource Conservation and Recovery Act (RCRA) Subtitle D that prohibits the addition of liquids to a waste management unit from outside the unit (40 CFR 258.28). Supplemental liquid addition is critical to the operation of the bioreactor landfill.
- The construction and operation/maintenance and costs associated with bioreactor landfills are not fully known.

RD&D Activities

- At the present time, bioreactor landfills are in the early stages of full-scale field testing. In the United States, early work on anaerobic bioreactors began in the mid-1980s at landfills in Sonoma County and Mountain View, California.
- Currently, over ten anaerobic and aerobic bioreactor projects (including hybrids) are in various stages of deployment or demonstration. The Environmental Protection Agency (EPA) Project XL program is currently implementing and evaluating five bioreactor landfills and developing a database to track and record information on bioreactor landfills. EPA also funded the development of a bioreactor operations training manual and training course.
- On March 22, 2004 EPA revised the Criteria for Municipal Solid Waste Landfills (MSWLF) to allow states to issue research, development, and demonstration (RD&D) permits for new and existing MSWLF units and lateral expansions. This rule will allow Directors of approved state programs to provide Municipal Solid Waste RD&D permits for new and innovative landfill technologies, such as bioreactor landfills.
- In 2001, DOE's National Energy Technology Lab funded a study of the Yolo County Pilot Bioreactor Landfill Demonstration (9,000-ton test cell and 9,000-ton control cell) to study new ways to capture greenhouses gases from the bioreactor landfill.

Recent Progress

- Results from the Yolo County pilot-scale demonstration project showed production of landfill gas in the anaerobic cell was more than six times that of the normal range expected. A tenfold increase in methane recovery rate was observed compared to conventional landfills, which suggest a tenfold reduction in interval of methane generation. The biodegradation rate of the waste was increased thus decreasing the waste stabilization and composting time (5-10 years) relative to what would occur within a conventional landfill (30 or more years).
- Benefits include:
  - Subtitle D established a "dry tomb" sanitary landfill approach to municipal solid-waste disposal, where waste is placed and maintained in dry conditions to minimize potential leachate and gas generation and release. A concern of the "dry tomb" landfill is that the waste may pose a threat to public health and the environment well beyond the prescribed 30-year, post-closure maintenance period because the natural decomposition process is retarded. Should the "dry tomb" landfill containment be compromised, significant generation and release of leachate and gas could occur well beyond the post-closure maintenance period. In a bioreactor landfill, controlled quantities of liquid are added and circulated through waste to accelerate the natural biodegradation and composting process of the waste. The bioreactor landfill process may significantly increase the biodegradation rate, such that the waste may be stabilized in a relatively short period of time (5-10 years).
  - Reduction in air-pollutant emissions, especially criteria pollutants and methane early in the decomposition process when landfill gas is collected and combusted.
  - The anaerobic bioreactor may increase gas yields to favor more economical utilization projects in the earlier years of the landfill life while reducing the greenhouse gas burden in the subsequent years. Gas generation during conventional landfilling techniques occurs over long periods of time (more than 30 years).
  - Aerobic technology (i.e., methane elimination) could become a prime candidate technology for landfills in the United States and elsewhere that cannot generate landfill gas in sufficient quality or quantity to economically recover the associated energy. In addition, the technology also could be considered as a follow-on technology for energy-recovery projects at landfills that are no longer producing methane at economically valuable levels.

Commercialization and Deployment Activities
• Several companies, including the largest waste management company in the United States, are working with states and the EPA to demonstrate bioreactor technology. **Market Context** • Municipal solid-waste landfills represent the largest human-made source of methane emissions in the United States (approximately 32%), and account for approximately 55% of waste disposal. • All new municipal solid-waste landfills constructed in the United States are potential markets. • Based on the preliminary findings from several bioreactor demonstration projects, landfill gas recovery costs on a $/MMBtu basis will be lower for a bioreactor landfill than for a conventional landfill. The cost reduction could be 25%-50%, depending on how bioreactor costs are allocated.

4.1.2 CONVERSION OF LANDFILL GAS TO ALTERNATIVE USES

Technology Description

Landfill gas to compressed natural gas vehicle refueling station, Los Angeles, California

Conversion to compressed natural gas (CNG) and liquefied natural gas (LNG): Use of landfill gas to produce CNG and LNG for vehicle use has gained interest because: (1) it provides an alternative use for landfill gas projects that cannot use all of the gas recovered; (2) rising fuel prices; and (3) increasingly stringent diesel emission regulations require use of alternative fuel vehicles. Use of CNG and LNG has been recognized for its environmental benefits because it is a cleaner-burning fuel relative to gasoline and diesel fuel, especially for NO_x and particulate matter (PM) emissions.

Pipeline quality gas and CO_2 production: Since landfill gas is about half CO_2 and half methane, separation of these two gases can generate two separate sources of revenue – commercial CO_2 and pipeline-quality (high-Btu) methane. Since methane is the chief constituent of natural gas, the methane from landfills, once cleaned and processed, can be fed into existing natural gas distribution networks. CO_2 separated from landfill gas can be processed to high-purity (food grade) liquid CO_2; coalbed, oil, and gas enhancement; wastewater treatment; dry cleaning; or for the production of dry ice; or to promote plant growth in greenhouses.

Conversion to methanol and ethanol: Landfill methane has been successfully converted to methanol and ethanol, both renewable fuels that produce fewer emissions than gasoline. Landfill gas can be converted to methanol and ethanol for use as a chemical feedstock, hydrogen production, or as a vehicle fuel or fuel additive.

System Concepts

- *Conversion to CNG/LNG:* In general, to produce LNG from landfill gas, the removal of corrosive trace impurities is accomplished through the use of phase separators, coalescing filters, and impregnated\non-impregnated activated carbon adsorbents. Next, a zeolite adsorbent removes remaining polar molecules (specifically water) to a concentration of a few parts per million. Oxygen also must be removed at this point, if present in more than trace quantities. The resultant gas then enters a cryogenic purifier where the carbon dioxide is separated out, leaving a high-grade LNG product consisting of 90%-97% methane. The remainder of the LNG is dissolved nitrogen. Conversion to CNG is a similar process and therefore not addressed here.
- *Pipeline quality gas production:* Landfill gas must be processed to increase its energy content and to meet strict standards for oxygen, hydrogen sulfide, moisture, carbon dioxide, and non-methane organic compounds. The landfill gas also must be free of environmentally unacceptable substances and must be pressurized to the pressure of the pipeline to which the gas production facility is interconnected.
- *Conversion to methanol and ethanol:* Nearly all methanol produced today is made from natural gas. Ethanol is produced primarily from biomass feedstocks. Similar to conversion to CNG/LNG, landfill gas is an alternative, renewable feedstock.

Representative Technologies

- *Conversion to CNG/LNG:* Thermal regenerative purification system.
- *Pipeline quality gas production:* At least three processes are employed to upgrade landfill gas to pipeline quality – membrane separation process, molecular sieve (pressure swing adsorption), and absorption process using a liquid solvent.
- *CO_2 production:* Triple-point crystallization and the use of cold liquid carbon dioxide.
- A CO_2 wash technology removes contaminants from landfill gas. The resultant clean stream of methane and CO_2 can be used as medium Btu gas or can be further refined into products such as CNG/LNG production, pipeline quality gas, and methanol.

Technology Status/Applications

- *Conversion to CNG/LNG:* To date, five landfill gas-to-CNG and LNG projects have been successfully demonstrated worldwide. Los Angeles County, California, has operated a CNG project at Puente Hills Landfill for more than five years. The CNG plant produces 3,500 psi natural gas equivalent as fuel for several pieces of landfill equipment (e.g., water truck). The first landfill gas-to-LNG pilot plant recently completed initial performance testing at the Burlington County Landfill in New Jersey. Landfill gas is being converted to LNG to fuel two solid waste collection vehicles. By 2006, the first commercial landfill gas-to-LNG production and fueling facilities are planned for landfills in California (2) and Pennsylvania (1).
- *CO_2 production:* Triple-point crystallization has been demonstrated. Use of cold liquid carbon dioxide is under development.
- *Pipeline quality gas production:* Eight projects that convert landfill gas to high-Btu (pipeline-quality) gas are currently in operation throughout the United States. An additional four projects are currently under construction, and three are in the planning stage
- Conversion of landfill gas to methanol and ethanol for use as a vehicle fuel or as a chemical feedstock has been investigated in the United States since the early 1980s. At least one methanol synthesis project using LFG is planned.

Current Research, Development, and Demonstration

R&D Goals

- *Conversion to CNG/LNG:* Monitor performance of LNG conversion technology application on landfill gas and converted vehicle performance; development of additional commercially available LNG vehicles (e.g., solid waste collection trucks); and development of distribution/fueling infrastructure.
- *Pipeline quality gas production*: Develop cost-effective separation technology applications.
- *CO_2 production*: Evaluate and demonstrate technologies for producing commercial carbon dioxide.
- When technologically feasible and cost competitive, LFG could offset natural gas consumption for the production of methanol and hydrogen.

RD&D Challenges

- *Conversion to CNG/LNG*: No commercial-scale, landfill gas-to-LNG facility is currently operational. Major drawbacks to using CNG in motor vehicles include the limited driving range of vehicles because of fuel storage capacity constraints. For both CNG and LNG, another limitation has been the availability of fuel dispensing facilities. In addition, the cost to convert vehicles from diesel to CNG/LNG is prohibitive.
- *Pipeline quality gas production*: The cost of the landfill gas clean-up technologies is such that this application is only feasible at the largest landfills (which produce greater quantities of landfill gas), where economies of scale can make projects cost-effective.
- *CO_2 production*: Costs to recompress the CO_2; the need to remove trace contaminants to meet purity requirements for food-grade use; and nontechnical hurdles, such as public perception of a food product developed from landfill gas.
- The major obstacle facing methanol and ethanol production from landfill gas has been the overall economics of the conversion technology and lack of suitable markets for the end product.

RD&D Activities

- *Pipeline quality gas production*: A study was recently completed under a EPA funded grant to investigate conversion of methane for pipeline gas production and CO_2 injection into coal seams beneath a landfill in West Virginia.
- *CO_2 production*: Field tests were conducted on producing commercial CO_2 from landfill gas at the Al Turi Landfill in Goshen, New York, with a grant from DOE's National Energy Technology Laboratory. A DOE Small Business Innovation Research grant helped fund a demonstration project to convert landfill gas into methane for fuel cell electric generation and pure carbon dioxide to stimulate greenhouse crop growth. Brookhaven National Laboratory is supporting a study that will remove landfill gas contaminants and produce LNG for vehicle fuel and liquid CO_2 from raw LFG at the Burlington County Landfill in New Jersey.

Recent Progress
• *Pipeline quality gas production:* Eight projects that convert landfill gas to high-Btu (pipeline-quality) gas are operating in the United States. An additional four projects are under construction and three are in the planning stage. • *CO_2 production:* Klickitat Public Utility District in Oregon will generate carbon offsets by use of landfill gas to produce green electricity. The project is expected to produce 2.1 MW of electricity and 13 ton/day of CO_2 while removing contaminants such as sulfur compounds, volatile organic compounds, and siloxanes. • Under a recently completed Small Business Innovation Research Phase II grant from DOE, Acrion Technologies Inc. successfully demonstrated the Liquid CO_2 Wash Process with a pilot-scale system at the Al Turi Landfill in Goshen, New York, and at the Burlington County Landfill in New Jersey. • The first commercial-scale application of the Liquid CO_2 Wash Process is under development at a landfill in Ohio.
Commercialization and Deployment Activities
• Currently, few companies manufacture the landfill gas-to-LNG conversion technology. • Commercial technologies exist for upgrading LFG to high Btu gas production; however this application is only feasible at the largest landfills. • Available methanol and ethanol conversion technology is limited and not currently cost effective. **Market Context** • Conversion of landfill gas to LNG or CNG may be ideally suited for medium- to large-scale landfills, especially with existing gas collection systems. Municipalities and private-sector companies that maintain medium- and heavy-duty vehicles (buses, trash collection, postal service, etc.) – especially in metropolitan areas – represent important markets. Trash collection vehicles average approximately 25,000 miles a year and get 3 miles per gallon of diesel fuel. • Commercial CO_2 markets include food and beverage and other industrial applications. • Pipeline gas and hydrogen production from large landfills.

4.1.3 ELECTRICITY-GENERATION TECHNOLOGIES FOR LANDFILL GAS

Technology Description

Several emerging alternative electricity-generating technologies have significant potential for landfill gas. *Fuel cells* and *microturbines* are technologies that are available in small incremental capacities, have short lead times from planning to construction, and have lower air emissions than other, larger-scale, generation technologies. The modularity of these technologies makes them ideal for use on landfill gas; by adding or removing units, project size can be adjusted to match landfill gas production. *Stirling-Cycle engines* – closed-cycle "hot air" engines – are adaptable for use with landfill gas, are highly efficient, and have low emissions as compared to reciprocating engines. The *Organic Rankine Cycle (ORC)* engine is a process that uses an organic fluid (rather than steam) in a closed cycle to convert thermal energy, such as an engine or flare burning landfill gas into mechanical energy resulting in essentially no air emissions. The ORC may represent a technically feasible alternative for electrical generation using landfill gas.

Three 30-kW microturbines are in use at a landfill in Burbank, California, to generate electricity.

System Concepts

- Fuel cells generate electricity through an electrochemical process in which the energy stored in a fuel is converted directly into electricity, thus avoiding the need for combustion. These units can run on hydrogen that is produced from the methane content in landfill gas and use oxygen from the ambient air. Landfill gas cleanup is an important issue as fuel cells employ catalysts that could be fouled by trace compounds in landfill gas.
- The microturbine is a derivative of the much larger combustion turbines employed in the electric power and aviation industries. Microturbines spin at much faster speeds than traditional combustion turbines.
- Both fuel cells and microturbines generate a significant amount of thermal energy that can be easily captured for use (i.e., hot water/steam), thus increasing the total efficiencies of these units.
- In the Stirling engine, gas is contained in a continuous, closed volume that is divided into hot and cold regions. The size of the volume is periodically varied to compress and expand the gas. Heating and cooling are accomplished by periodically transferring working gas between the hot and cold regions. Since the engine derives its heat from an external source, almost any type of fuel (e.g., landfill gas) or combustible material can be used.
- The Organic Rankine Cycle (ORC) engine is a process that uses fluid in a closed cycle to convert thermal energy, such as a engine or flare burning landfill gas, into mechanical energy (e.g., electricity).

Representative Technologies

- Microturbines currently on the market use air bearings rather than traditional mechanical bearings in order to reduce wear. Combustion air and fuel are mixed in a combustor section, and the release of heat causes the expansion of the gas. Hot gas is sent through a gas turbine that is connected to a generator. Units are normally equipped with a recuperator that heats combustion air using turbine exhaust gas in order to increase the unit's overall efficiency. Combustion air is compressed using a compressor that is driven by the gas turbine. Use of landfill gas requires gas compression.

Technology Status/Applications

- Several types of fuel cells using different electrolytes are either available or under development. The four basic electrolyte types are: (1) phosphoric acid, which is commercially available and has been demonstrated commercially on landfill gas; (2) molten carbonate, which has also shown promise for landfill gas use; (3) solid oxide; and (4) proton exchange membrane (polymer-membrane).
- The microturbine is a recently commercialized technology. Sixteen microturbine projects (10 megawatts) are

operational, and at least one additional project is under construction.

- Since January 2003, the first successful demonstrations of 2-25 kW and 10-25 kW Stirling-Cycle engines using landfill gas are operational at two landfills in Michigan. A Stirling engine also became operational in March 2005 at a landfill in Texas to supply electricity to a biodiesel project.
- Since 2004, two Organic Rankine Cycle demonstration projects have been operational at landfills in Texas and Illinois. The project in Austin, Texas, captures waste heat from a LFG flare and uses it to generate 200 kW of electricity. The Danville, Illinois, project involves exhaust heat recovery from three LFG-fired reciprocating engines to generate 200 kW of electricity.

Current Research, Development, and Demonstration

RD&D Goals

- Evaluate and demonstrate use of landfill gas as a fuel source for fuel cells and appropriate and cost-competitive cleanup technologies.
- Demonstrate long-term performance of microturbines on landfill gas, improve component corrosion protection, and develop larger microturbines.
- Demonstrate Stirling-Cycle and Organic Rankine engines at additional landfills; and evaluate technical (e.g., O&M), economic, and environmental considerations by 2006.

RD&D Challenges

- For fuel cells, developing cleanup technologies for landfill gas that are adequate but not cost prohibitive.
- For microturbines, dealing with potential fouling and failure of the turbine unit from silica or other components in landfill gas, and potential corrosion and excessive wear of components due to constituents found in landfill gas. In addition, microturbines are not currently cost competitive with traditional reciprocating engines. The total cost of power production, based on net power output and assuming retirement of the capital cost during 10 years at an interest rate of 10%, would be $0.07–$0.14/kWh ($0.04-$0.06 for recip. engine).
- High cost to demonstrate Stirling engine and Organic Rankine engine; no commercial-scale units have been designed or demonstrated.
- Continued testing and commercialization of fuel cell and microturbine technologies.
- Technologies/processes to pretreat landfill gas prior to introduction to fuel cells and microturbines.
- Development of larger microturbines (i.e., greater than 75 kW).
- Development of larger Stirling engines and continuing to test Stirling and Organic Rankine Cycle technologies.

RD&D Activities

- EPA-funded phosphoric acid fuel cell demonstration on LFG in California; the same system was also demonstrated in Connecticut. DOE/EPRI funded a molten carbonate fuel cell on LFG; EPA funded a study to evaluate LFG cleanup technologies for use with fuel cells; and a DOE small-business innovative research grant funded a demonstration converting LFG to methane for fuel cell use.
- Three microturbine demonstration projects with landfill gas have been completed since October 1999 – a 75-kW unit in New Mexico and California, and a 30-kW unit in California. In 2000, EPA funded a demonstration of a microturbine on landfill gas in Oregon. In 2001 and 2002, EPA funded two additional microturbine demonstration projects in Virginia and Vermont to test new microturbine technologies.
- Today, one manufacturer is developing commercially viable Stirling engines versions for landfill application (up to 250 kW). One manufacturer is developing a commercially viable Organic Rankine engine for landfill application (200 kW).
- Since 1999, the Salt River Project (led by DOE and a municipal utility located in Phoenix, Arizona) is demonstrating the operation of the first thermal hybrid-electric sundish. This technology combines solar thermal heliostats and a Stirling cycle engine using landfill gas (dual "fuel" Stirling cycle engine).

Recent Progress
• A 200 kW phosphoric acid fuel cell is currently operating on landfill gas from the Braintree, Massachusetts, landfill. • Microturbines have been demonstrated to operate on landfill gas with a low methane content, and have demonstrated NO_x emissions less than one-tenth those of the best performing reciprocating engines • Demonstration of the first thermal hybrid-electric sundish (combines solar and Stirling cycle engine using landfill gas) has been running successfully since 1999. • Since January 2003, the first successful demonstrations of 2-25 kW and 10-25 kW Stirling cycle engines using landfill gas are operational at two landfills in Michigan.
Commercialization and Deployment Activities
• Phosphoric acid fuel cells are commercially available today, and many are installed worldwide. Most are using fuels other than landfill gas, but this type of fuel cell has been successfully demonstrated on landfill gas. Molten carbonate fuel cells have been operated on landfill gas – as well as a variety of other fuels – and this type of fuel cell looks particularly promising for landfill gas application due to its tolerance of CO_2 . • At least two companies manufacture and sell microturbines for landfill gas applications (30 kW – 200 kW); 16 commercial microturbine projects (10 megawatts) fired by landfill gas have been operational since January 2002. • Several landfill gas pilot-plant studies have been conducted for Stirling technology, and two ORC pilot projects are operational. **Market Context** • A market for these technologies exists wherever there is a need for electricity generation capacity. Hundreds of thousands of landfills and open dumps exist worldwide, all of which generate some amount of methane that could be used as a local energy resource for communities. Efforts to improve the cost effectiveness of these technologies will allow for greater landfill market development.

4.1.4 ADVANCES IN COAL MINE VENTILATION AIR SYSTEMS

Technology Description

Lean fuel turbine running off of ventilation air methane and drained gas. (Courtesy of Energy Developments Ltd.)

Ventilation air methane equipment (Megtec Vocsidizer) in Australia. (Courtesy of BHP Billiton Ltd).

Gassy underground coal mines emit more than 35 million tonnes (metric tons) of CO_2 equivalent (MtCO2e) of methane through their ventilation shafts. Until recently, because of the very low concentration (typically below 1%) of methane in ventilation air, coal operators had no technically proven option to recover this gas for its energy value. However, during the past decade, technologies have been developed and adapted that offer the promise of mitigating most of these emissions at low cost. One family of technologies being developed is the catalytic and thermal flow reversal reaction of ventilation air methane. These technologies may use up to 100% of the methane from ventilation shafts, and the byproduct heat may be used for the production of power or to satisfy local heating needs. Another prospective technology allows for the direct use of air mixed with down to 1% methane to produce power in gas turbines. This approach may require enriching the concentration of the air flow but may be a lower capital cost means of producing power.

System Concepts

Flow Reversal Reactors

Both catalytic and thermal-flow reversal technologies employ the principle of regenerative heat exchange between a gas and a solid bed of heat-exchange medium. Ventilation air flows into and through the reactor in one direction, and its temperature increases until the methane is oxidized. Then the hot products of oxidation lose heat as they continue toward the far side of the bed, until the flow is automatically reversed.

- Thermal reactors operate above the auto-ignition temperature of methane (1,000ºC). Catalytic reactors reduce the auto-ignition temperature significantly.
- Both types of reactors produce heat, which, through use of heat exchange technologies, may be transferred for local heating needs or for the production of power in steam or gas turbines.

Lean Fuel Turbines

- Some lean-fuel turbine concepts employ catalysts to aid the combustion.
- Others take place in an external combustor without catalysts but at a lower temperature than with normal turbines.
- Depending on the methane concentration, these technologies may use ventilation air for more than 80% of all fuel if concentrations are high, or less than 20% with low concentrations.

Representative Technologies

- Thermal-flow reversal reactors require a higher auto-ignition temperature that may require more sophisticated heat-exchange technologies.

- Catalytic flow reversal reactors have a lower auto-ignition temperature that may make heat exchange less costly, but they require catalyst material.
- Lean-fuel turbines under development include microturbines and larger scale turbines.
- Ancillary uses for ventilation air methane exist, such as the use of some ventilation air methane as the combustion air for power projects. This approach is technically straightforward and commercially proven, but the greenhouse gas reduction potential is limited.

Technology Status/Applications

- The Environmental Protection Agency (EPA) has identified and evaluated two specific flow reversal reaction technologies. Based on laboratory and field experience, both technologies may sustain operation with ventilation air with methane concentrations as low as 0.1%.
- These reactors have been applied for oxidation of volatile organic pollutants and have been successfully tested at small scale with ventilation air methane. In addition, the thermal reactor has been tested at field-scale in Australia. The first commercial thermal oxidation project is in development and should in operation by the fourth quarter of 2005. Both thermal and catalytic flow reversal technologies may be used for the simple oxidation of methane (reducing methane emissions); and for the heat product, which may be used for production of power, direct heating or cooling.
- The EPA is working with technology vendors to identify viable lean fuel turbines and to improve their applicability for real-world ventilation air methane projects and identifying sites and partners for field demonstration. The EPA is also exploring an array of technologies for the use of ventilation air methane.

Current Research, Development, and Demonstration

RD&D Goals

- First commercial-scale field unit to demonstrate oxidation-only in 2005, and in the US in 2006 and 2007.
- First commercial-scale field unit to demonstrate oxidation and heat recovery (power) in 2007 and 2008.
- A program of market penetration to be undertaken 2005-2010, ultimately leading by the end of the program to the majority of ventilation air methane emissions mitigated.

RD&D Challenges

- The first commercial-scale thermal oxidation unit is expected to be in operation by fourth quarter 2005 in Australia, but there have not been any commercial-scale catalytic oxidation unites designed or demonstrated on a field or commercial scale.
- Heat-recovery technologies must be adapted from other industries for application at mine ventilation shafts.
- Safety design issues need to be addressed.

RD&D Activities

- Several technology developers/vendors are working with the coal industry, EPA, and DOE to develop the first commercial-scale projects.
- Evaluate performance of first commercial project in Australia.
- EPA is providing technical support for technology vendors in identifying markets, performing safety analyses, and supporting project development.
- EPA and DOE are working with CONSOL Energy, a large coal operator, to demonstrate thermal oxidation of ventilation air methane using Megtec's Flow Reversal Reactor.

Recent Progress

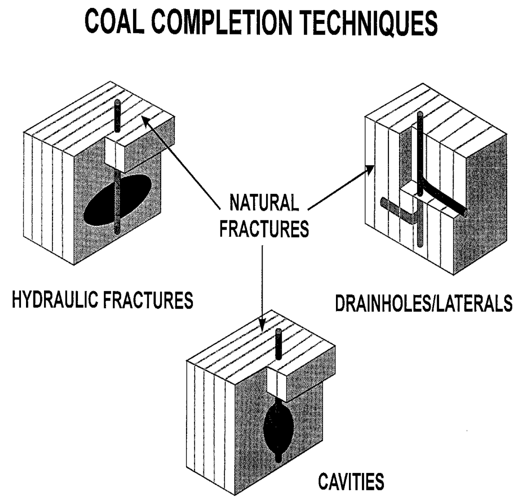
- A project in Australia commercially employed ventilation air methane as feed air in internal combustion engines. The ventilation air methane provided approximately 7% of the total energy for the project at nominal cost.
- Tests prove that flow-reversal reactors can successfully sustain reactions down to a methane concentration in air of 0.1%.
- Small-scale demonstrations at coal mines have shown that ventilation air methane can be safely deployed at noncommercial scale, and that heat recovery is technically viable.

Commercialization and Deployment Activities
• Project vendors and developers are working with coal operators to develop ventilation air methane projects in the United States. **Market Context** • Majority of emissions in the United States at fewer than 30 very gassy ventilation shafts. • Heat recovered likely will interest power generators. Potential for more than 450 MW of power production available and equipment market of over $1 billion. • Markets for these technologies exist worldwide in countries with gassy coal seams and coal mining industries such as Australia, China, India, Mexico, Ukraine, Russia, Kazakhstan, Germany, United Kingdom, and Poland.

4.1.5 ADVANCES IN COAL MINE METHANE RECOVERY SYSTEMS

Technology Description

In-mine directional drilling.



Vertical drainage in advance of mining.

Coal mine methane (CMM) is liberated into underground coal mines – as coal seams are mined – and vented out of the mine to provide a safe working environment. Where ventilation air cannot adequately control these emissions, mine operators utilize a CMM drainage system. Drainage systems consist of boreholes drilled into the coal seams and adjacent strata, and equipment is used to extract and collect CMM. Dependent on geologic, reservoir characteristics, and mine layout, CMM can be recovered in advance of mining or after mining has occurred. State-of-the-art CMM drainage techniques are now available to mine operators. Advances in steerable motors and stimulation techniques have increased the ability to recover CMM far in advance of actual mining operations. This allows operators to recover a higher percentage of the total methane in coal seams. The most promising technologies either necessitate fewer wells to produce more gas or increase the recovery efficiency of surface wells or underground boreholes. This CMM, much of which is high quality, presents many alternatives for utilization and markets.

System Concepts

- Boreholes are drilled into the coal seams and adjacent gas-bearing strata vertically or horizontally from the surface or from within the mine, depending on geologic, reservoir, and mine design and conditions.
- Various drilling technologies are employed to promote the release of the CMM.
- Gathering systems are used to collect and vent the CMM or distribute the gas to a specific use such as a natural gas pipeline. CMM recovered through drainage systems would have otherwise been vented through mine ventilation systems.

Representative Technologies

- Directional drilling systems that enable fewer wells to contact the same quantity of coal.
- Advanced stimulation techniques that use injection of a second gas such as nitrogen to improve recovery.

Technology Status/Applications

- Directional drilling, applied in conjunction with flexible coiled tubing and high pressure water jets, has been downscaled and applied to coalbed methane reservoirs.
- Operators also have demonstrated and commercialized slant-hole directional drilling, which involves the drilling of a guided surface hole that intersects the targeted coal seam and continues drilling within the bounds of a coal seam.

- Recent innovative methods for enhancing the recovery of methane from coalbeds by injection of second gases such as nitrogen are being tested. Carbon dioxide, while potentially attractive for unmineable seams, is not appropriate for coalbed methane development associated with mining because CO_2 is a hazard in the underground mining environment. Further work regarding the use of nitrogen is required.
- Computer simulation has suggested various configurations of in-mine directionally drilled boreholes and surface vertical wells to optimize CMM drainage approach.

Current Research, Development, and Demonstration

RD&D Goals

- Refined directional drilling technologies to improve the application in friable coal seams, increase drilling depths, and reduce the cost of drilling.
- Application of in-mine hydraulic fracturing techniques.
- Additional data supporting nitrogen injection as a cost-effective alternative for improving recovery efficiencies.
- In-mine application of nitrogen-injection techniques.
- Use of other inert gases as a second gas for injection into mined coal seams.
- New drilling techniques that could improve recovery of coalbed methane.
- Further applications of surface oil and gas drilling, as well as completion technologies and their application for in-mine CMM recovery.

RD&D Challenges

- Must locate demonstration projects at coal mines to clearly establish greenhouse gas reductions, but the number of very gassy mines in the United States is limited to about 30-40 coal mines.
- Must develop products that the mining community considers a help rather than a hindrance.
- Must directly link gas recovered to methane emissions avoided. Total coal mine methane emissions (ventilation air methane and drained emissions) does not increase due to improved drainage technologies; rather, ventilation air emissions decrease when drained gas emissions increase. Must consider this when assessing total methane emissions at a specific project.

RD&D Activities

- Several U.S. companies have developed directional drilling techniques, both vertical and horizontal, which are currently being evaluated.
- Use of CO_2 and nitrogen have been laboratory tested and/or field tested by private industry and research institutes.
- U.S. government funding has focused on gas utilization techniques, rather than recovery enhancement.

Recent Progress

- Reports indicate that directional drilling and injection of a second gas have demonstrated drainage efficiencies of 50%-90%.
- Slant-hole drilling has been used successfully to date at the SASOL Secunda Operations in South Africa. SASOL Secunda has drilled in excess of 100,000 meters of the surface to in-seam wells, regularly reaching target depths of up to 2 km. Dallas-based CDX Gas has successfully commercialized a surface directional drilling technique called the "Pinnate" multilateral drainage networks, and a dual-well drilling and production system.
- Nitrogen tests appear to be successful, but results are confidential.
- If the national, industry-wide drainage efficiency at underground mines increased from the current average of 34%-50%, then the United States could realize an additional 8 $MtCO_2e$ emissions reductions.

Commercialization and Deployment Activities
• Projects in the United States are currently employing directional drilling on a limited basis. • Carbon dioxide injection has been used for enhanced oil production for quite some time, and is being evaluated by the Alberta Research Council and an international consortium of Canadian and U.S. organizations. The results are confidential at this point. CO_2 injection does not appear appropriate for coal mine applications, however. • Nitrogen injection to enhance methane recovery from mineable coal seams needs demonstration. **Market Context** • Gassy coal mines in the United States, where improved gas recovery efficiencies will yield greater coal mine productivity and natural gas for use or resale are potential markets for this technology. • Additional gas recovered likely will interest gas users such as gas marketers, power generators, etc. • Markets for these technologies exist worldwide in countries with gassy coal seams and coal-mining industries such as Australia, China, India, Ukraine, Russia, Kazakhstan, Germany, the UK and Poland. • Beyond carbon reductions, market for these products will be found in the exploration and production sector of the natural gas industry.

4.1.6 MEASUREMENT AND MONITORING TECHNOLOGY FOR NATURAL GAS SYSTEMS

Technology Description

Handheld infrared remote imaging spectrometer for fugitive gas leak detection.

Hi-Flow™ Sampler to measure emission rates.

There are approximately 300,000 miles of pipeline in the U.S. natural gas transmission network. Along this network, compressor stations – with up to 2,500 separate components each – leak hundreds of millions of dollars worth of methane into the atmosphere every year. In addition, there are more than 700 gas-processing facilities that lose an estimated 30 billion cubic feet of gas each year. Through the use of effective leak detection and measurement technology as part of a directed inspection and maintenance program, methane emissions can be reduced significantly.

System Concepts

- Advanced leak detection and measurement technologies enable quick and cost-effective detection and quantification of fugitive methane leaks.
- Directed inspection and maintenance programs employ these technologies through the collection of screening and measurement data using comprehensive surveys in the first year. Information gathered on equipment with high leak rates is then used to direct surveys and prioritize cost-effective leak repair efforts in subsequent years. Because leak surveys and repairs are better focused and more accurate, they can be conducted less frequently, thereby reducing operation and maintenance costs.

Representative Technologies

- The Gas Technology Institute (GTI) has developed an advanced measurement technology known as the Hi-Flow™ Sampler. This technology is unique because it measures actual emission rates from sources that traditionally were not easily measured. The Hi-Flow™ utilizes a variable-rate induced-flow sampling system that provides total capture of the emissions from a leaking component. The instrument is designed to ensure total emissions capture, and prevent interference from other nearby sources. A dual-element hydrocarbon detector (i.e., catalytic-oxidation/thermal-conductivity), measures hydrocarbon concentrations in the captured air stream ranging from 0.01% to 100%. A background sample-collection line and hydrocarbon detector allows the sample readings to be corrected for ambient gas concentrations. A thermal anemometer monitors the mass flow rate of the sampled air-hydrocarbon gas mixture, and a mass rate is then calculated.
- GTI (in cooperation with Pacific Advanced Technology) is also developing advanced leak-detection technology. One of the emerging technologies is the IMSS camera, a handheld infrared remote imaging spectrometer for fugitive gas leak detection. It detects species by comparing differential absorption spectra. The device can detect low flow and underground methane leaks from a maximum of 300 feet away but is more effective at a distance of about 50 feet or less. Other hydrocarbon optical imaging technologies are now available for use.

Technology Status/Applications

- Traditional leak measurement technologies are currently available. Advanced technologies, like the Hi-Flow Sampler, are in the demonstration and deployment stage.
- Advanced imaging technology for leak detection is now in the advanced demonstration phase. Next-generation technology may provide the ability to both detect a leak and quantify the emission rate.

Current Research, Development, and Demonstration

RD&D Goals

- Complete the development of advanced measurement technologies like the Hi-Flow™ and ensure broad deployment throughout the industry.
- Advance the development of imaging technology for methane leak measurement and facilitate demonstration and deployment.

RD&D Challenges

- Advance imaging technology to quantify methane losses

RD&D Activities

- Advanced measurement technologies already are being demonstrated. Additional research to enhance this technology is underway.
- Identification and adaptation of new technologies for real-time remote optical leak detection, quantification, and speciation is underway. Preliminary testing indicates the ability to image low-flow conditions and under-ground methane leaks.
- The Kansas State University National Gas Machinery Laboratory and EPA's Natural Gas STAR Program are collaborating on a study to demonstrate the cost-effective use of measurement technology to reduce methane leakage from natural gas production and processing facilities.

Recent Progress

- As part of a cooperative R&D effort among the EPA, the Gas Technology Institute, and the natural gas industry, the effectiveness of utilizing the Hi-Flow™ Sampler measurement technology to reduce methane leakage at three gas-processing plants was evaluated. The value of natural gas losses at the surveyed sites was approximately $2.2 million, substantially offsetting the cost of the surveys.
- Preliminary testing of the IMSS technology for leak detection has been successful. In a recent test conducted by PAT, IMSS successfully imaged leaks as small as 0.01 cubic feet per minute in ambient conditions, using either a building or the sky as background.

Commercialization and Deployment Activities

- The Hi-Flow**™** is being used by several large production, processing and transmission companies.

Market Context

- Gas production, transmission and processing companies are most likely to be interested in these technologies.