Appendix A to FAR 99-04

ENERGY INNOVATIONS SMALL GRANT (EISG) PROGRAM

EISG FINAL REPORT

PROCESS FOR CONVERTING SEWAGE SLUDGE AND MUNICIPAL SOLID WASTES TO CLEAN FUELS

EISG AWARDEE

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Legal Notice

Inquires related to this final report should be directed to the Awardee (see contact information on cover page) or the EISG Program Administrator at (619) 594-1049 or email eisgp@energy.state.ca.us.

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EISG Awardee

This project was awarded to ENVIRONMENTAL ENERGY SYSTEMS INC. (EESI) of Santa Fe, NM. The Company is registered with the Secretary of State of California as Worldwide ENVIRONMENTAL ENERGY SYSTEMS INC. (wwEESI) in accordance with California law.

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Abstract

The purpose of this project was to research the feasibility of a supercritical water gasification (SCWG) process to convert compost made from municipal solid wastes and sewage sludge to clean energetic gases without oxygen. The goal is to reduce fuel costs for gas turbine combined cycle (GTCC) power plants and to improve both efficiency and environmental performance of existing steam power plants.

A lab-scale tubular reactor system was tested without oxygen at General Atomics (GA) in San Diego to convert compost to clean gases. Compost was prepared in a commercial aerobic digester and cured for odor-free handling and shipment. Test conditions were above the supercritical conditions of water, 221 bar (3205 psia) and 374 C (705 F). A high-density pumpable and stable slurry of over 40 wt.% solids was prepared at GA. The tubular reactor converted over 98% of the carbon in the slurry to hydrogen, methane, hydrocarbons and carbon oxides in less than one minute. No tar formation or corrosion of the equipment was observed.

A computer simulation model was prepared to simulate a hybrid power system. It predicts 62% thermal efficiency with minimum emissions and zero liquid effluents. Preliminary life-cycle cost analyses predict that electricity costs can be reduced to less than $50/MWh by retrofitting to existing natural gas fired combined cycle plants for base load service.

A pilot plant is planned to test the reactor tubes at full size. Development promises to reduce fuel costs, while solving waste disposal problems for California and worldwide applications.

Key Words:

Biomass, compost, supercritical water, slurry, gasification, sewage sludge, refuse

Executive Summary

Introduction

Most new power plants being installed in California are Gas Turbine Combined Cycle (GTCC) plants that burn increasingly expensive natural gas to produce electricity at up to 60% efficiency. These plants can be installed in less than half the time and at less than half the cost of new coal-fired plants and Integrated Gasification Combined Cycle (IGCC) plants that use cheap dirty fuels, but are less than 42% efficient. A new system is needed to adapt the new plants to cheaper fuels, while maintaining their efficiency and environmental performance.

This project researched the feasibility of using a supercritical water gasification (SCWG) process to convert compost made from municipal solid wastes and sewage sludge to clean energetic gases without oxygen. The expectation is to reduce the fuel costs of GTCC plants and to improve both efficiency and environmental performance of existing steam power plants.

Objectives

1. Determine the feasibility of using SCWG to gasify composted municipal solid waste/sludge, consisting of at least 23 wt% solids, with a minimum 96% conversion of carbon to gas.
2. Verify through visual inspection that no significant erosion, corrosion and deposition occurred inside the bench-scale system.
3. Assess the feasibility of recycling resulting liquids for zero liquid effluents.
4. Update and validate simplified thermodynamic computer simulation and life cycle cost models that can be used to predict system performance with various fuels.

Outcomes

1. Use of SCWG to gasify composted municipal solid waste/sludge is feasible by a wide margin:
    - We produced pumpable slurry mixture containing 40 wt% solids, exceeding the target goal by 74%.
    - The bench-scale system converted over 98% of the carbon in the slurry to energetic gases, including clean pressurized methane, hydrocarbons and carbon oxides in less than one minute, which is twice as fast as the target time.
2. No noticeable erosion, corrosion or deposition was observed in the test equipment.
3. Total suspended solids in the liquid effluent was less than 10%, supporting the feasibility of recycling liquids for slurry preparation after filtering to provide a “zero effluent” design. No toxic materials were produced that would limit disposal of the residue in a landfill.
4. A thermodynamic computer simulation model and a life cycle cost model were prepared and compared to an ASPEN simulation prepared for U.S Patent 5,280,701; however, there was insufficient funding in the current project to validate the models over a range of inputs, including the test data. Equilibrium compositions were assumed to be sufficiently

close to expected commercial operations to provide preliminary predictions of system performance. Results of the computer simulations included:

- Projected 62% thermal efficiency to electric power for the entire proposed hybrid plant. Projected efficiency for application to an existing steam power plant is over 50%.
- Projected capital costs of $1,100/kWh for a new hybrid plant, with projected cost of baseload power generation at $100/MWh.
- Projected capital costs of $500/kWh for retrofit to an existing GTCC plant, with projected cost of baseload power generation at $50/MWh.
- Retrofits for repowering existing boiler plants are competitive with GTCC plants burning natural gas at over $3.00/million Btu.

Conclusions

1. The test results support the continued investigation of composted municipal waste as an economical fuel source for GTCC and existing steam power plants.
2. We demonstrated that compost made from municipal solid wastes and sewage sludge can be made into slurry with 40 wt% solids, which significantly increases the range of applications, including the production of valuable byproducts, such as hydrogen. This mixture tended to clog in the ¼ inch preheater tube which was completely alleviated by changing to 3/8 inch tubing. This problem is not expected in larger tubes.
3. The project successfully demonstrated that the compost slurry can be used in a SCWG process to produce energetic gases and steam, including approximately 35% gaseous hydrocarbons and hydrogen, the largest fraction being methane. The remaining 65% of the carbon in the feed was converted mainly to CO_2 and a small amount of CO. The CO_2 can be separated for reduced emissions. It is unknown what effect compost grinding had on residence time for gasification. It is also unknown what impact scaling up the reactor tubes will have on the SCWG process.
4. Sufficient yield data was collected to determine gas composition, perform a carbon balance and perform a preliminary evaluation of recycling liquids after filtering for slurry preparation. While no corrosion, erosion or deposition was observed after running the tests, the tests conducted were not designed to accurately assess those effects over long-term testing.
5. Based on residence time and projected full scale reactor tubes, a standard module of 100 reactor tubes in a heat recovery steam generator (HRSG) per 25 MW turbine can consume an estimated 170 tons of composted municipal solid waste per day, reducing it to approximately 34 tons of inorganic residue.
6. The results of the preliminary computer simulation models are encouraging in terms of supporting an economic case for commercialization; however, the models include many assumptions that remain to be validated.

Benefits to California

This project contributed to the Public Interest Energy Research (PIER) program objective of reducing the cost of California electricity through the use of inexpensive biomass fuels. The project also contributed to the PIER objective of reducing environmental risk by diverting waste streams away from landfills.

Successful commercialization of SCWG technologies could promote business opportunities in several industries, including process development, waste disposal, electrical generation, pollution control and transportation fuels.

Recommendations

The next step is to assess the regime of slurry concentrations by conducting tests over the useful range using full-scale HRSG reactor tubes. Full-scale tubes are being installed in a new pilot plant under construction at General Atomics in San Diego. Test to determine the following:

1. Identify the optimum concentration of slurry that can be successfully gasified in full size reactor tubes,
2. Identify the optimum level of grinding required (if any) for trouble free gasification in full size reactor tubes,
3. Confirm slurry distribution in a 10-tube inlet manifold for scaleup to a commercial plant,
4. Confirm that the energy balance for SCWG does not change as a result of using full size reactor tubes,
5. Evaluate the longer-term potential for corrosion, erosion or deposition,
6. Test condensate for yield and quality and cleaning methods for recycle to slurry preparation,
7. Test ash for beneficial use or land filling,
8. Test mild operating conditions for byproduct yields and quality, including liquid hydrocarbons and carbon,
9. Refine computer models and economic feasibility analyses for retrofit to existing gas turbines and boilers, and
10. Collect and test fuel gases for combustibility in existing gas turbines, fuel cells and boilers.

Introduction

The purpose of this project was to research the technical and economic feasibility of a supercritical water gasification (SCWG) process to convert compost made from municipal solid wastes and sewage sludge to clean energetic gases in an anaerobic environment. The goal is to reduce the fuel costs of gas turbine combined cycle (GTCC) power plants and to improve both efficiency and environmental performance of existing steam power plants. Based on the use of renewable fuels, this project primarily supports the Renewable Energy Technologies PIER subject area.

The specific SCWG process investigated in this project was the patented Vapor Transmission Cycle (VTC) in which a slurry mixture is pumped under high pressure and temperature through specially designed heat recovery steam generator (HRSG) tubes situated in the exhaust of a gas turbine such that SCWG parameters are achieved within the tubes. Physical testing was conducted in an existing bench scale system at General Atomics (GA) facilities in San Diego, coordinated by the Principal Investigator.

A slurry mixture of composted municipal wastes and sewage sludge, generated from a conventional digester, was used in the bench scale system to establish the yields of generated gases and liquid effluent. The data generated was then used to update the computer modeling, life cycle cost analysis, and comparison of the proposed process with published information from competing processes. Based on an analysis of the data, this project was successful in establishing concept feasibility with sufficient confidence to warrant follow-on testing of the process in an advanced continuous-flow pilot plant. Successful operation of a continuous-flow plant would provide sufficient support for commercialization.

Project Objectives included:

1. Determine the feasibility of using SCWG to gasify composted municipal solid waste/sludge, consisting of at least 23 wt% solids, with a minimum 96% conversion of carbon to gas.
2. Verify through visual inspection that no significant erosion, corrosion and deposition occurred inside the bench-scale system.
3. Assess the feasibility of recycling resulting liquids for "zero effluent" design.
4. Update and validate simplified thermodynamic computer simulation and a life cycle cost models that can be used to predict system performance with various fuels.

The patented process under study, described in U.S. Patents 5,280,701 & 5,339,621, is named the Vapor Transmission Cycle, (VTC), and incorporates the SCWG process. In the Vapor Transmission Cycle, HRSG tubes are modified to distribute slurry and transfer sufficient heat to meet SCWG heat requirements without oxygen addition, including raising the temperature of the slurry to saturation, vaporization, and chemical reactions. The tubes are designed to accept slurry solutions containing minerals and metals without corrosion and deposition on heat transfer surfaces, up to and including the supercritical conditions of water, above 221 bar (3205 psia) and 374 ^oC (705 ^oF). The tubes must be of sufficient length to provide adequate residence time and surface area to allow reactions to occur. A commercial method of fluidized particle scrubbing is used to improve heat transfer and prevent corrosion and deposition on heat transfer surfaces.

The HRSG reactor tubes are designed to generate clean fuel gases, CO_2 and steam for GTCC power plants by feeding water slurries or emulsions above about 20% organics, including heavy oil, coal fines, bitumen, tar sands, biomass, compost, crumb rubber and sludges.

Supercritical steam generators have been developed to increase the efficiency of coal fired power generation up to 40%. Steam is produced in tubes by a smooth transition to vapor at less than 1/10 of the density and more than ten times the velocity of the feedwater. Figure 1 illustrates the temperature and density relationships of water at selected pressures.

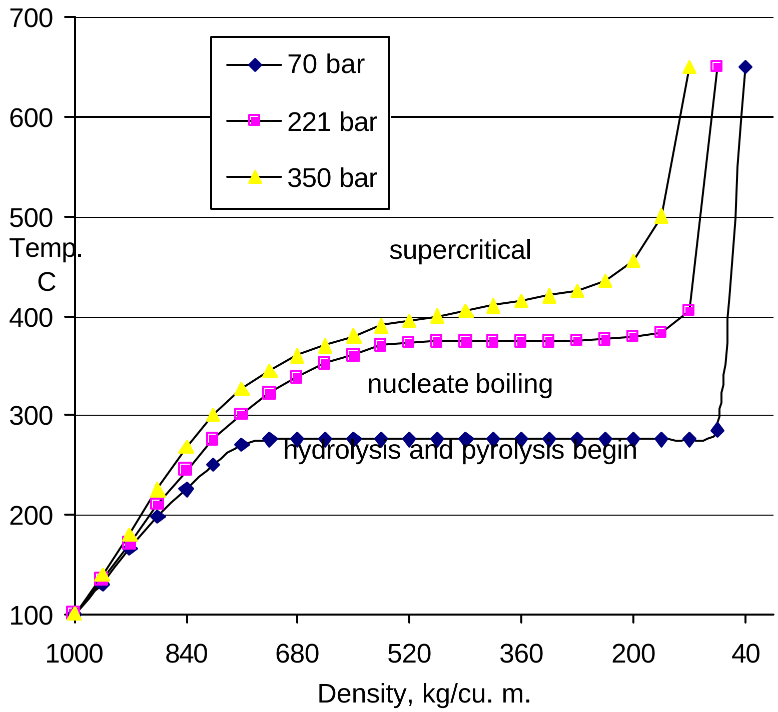

Fig. 1 Temperature vs. density for water at various pressures

The HRSG tubes depend on external heat transfer through a containment surface to a pressurized fluid that can contain a solvent (water), dissolved or emulsified materials, or slurry. The water can contain organic materials, granular media, catalysts, and pH control reagents. Inorganic materials can include sulfur, chlorine, fuel nitrogen, alkali metals, ash, vanadium and other metals. When chlorine is present it can react to form hydrochloric acid, which would preclude the use of low-alloy system components in high temperature areas.

The qualities of many supercritical solvents, including hydrocarbons and carbon dioxide (above 31 C and 74 bar) are well known, cost-effective, and in commercial use for cleaning and selective separations of organics. Water, the most important solvent in nature, has fascinating properties as a reaction medium in its supercritical state, where it behaves very differently from water at standard conditions. Supercritical water, above 221 bar (3205 psia) and 374 C (705 F), dissolves organics and precipitates inorganic materials, as shown in Figure 2. The solvent advantages of inorganic supercritical fluid solvents (e.g., water and CO_2) over conventional organic solvents, and the application of supercritical fluids for complex matrix interactions have been reported (Hawthorne, 1994).

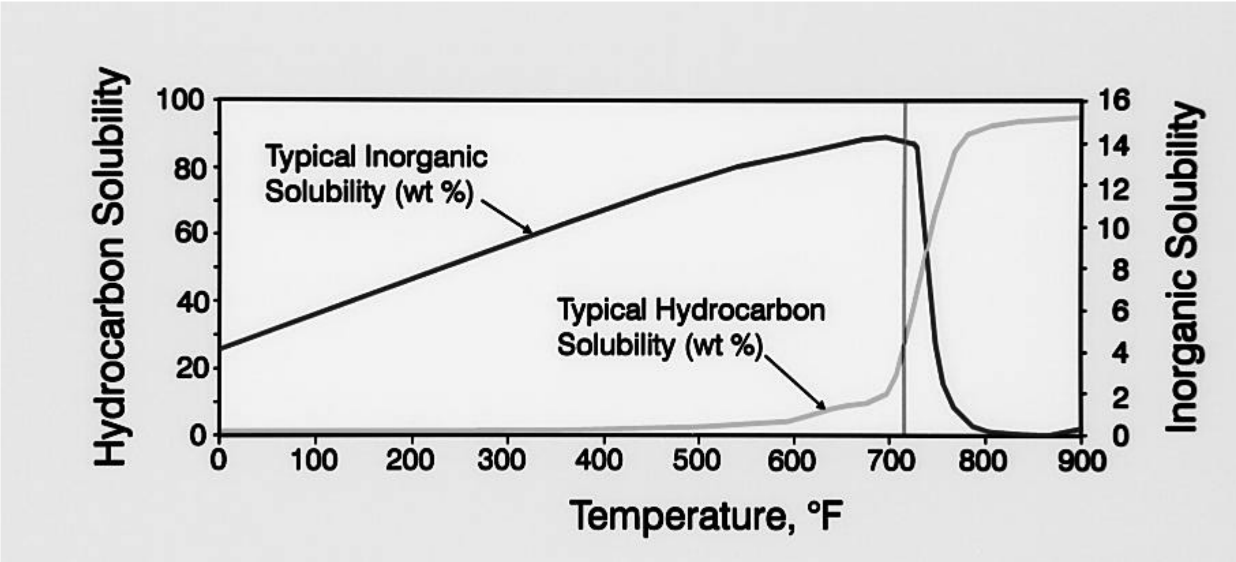

Fig. 2 Water Solvency at 221 bar (3205 psia)

The polarity and solvent qualities of water can be controlled by temperature and pressure. Most organic materials dissolve in all proportions in supercritical water. Unsaturated metal centers may be able to coordinate with organic target molecules, thereby catalyzing degradation of the targets in supercritical water (Sealock, 1996). In addition, the presence of a second solute such as carbon dioxide produced by these reactions may augment supercritical water solvency.

Regardless of its pressure, supercritical steam gasifies organic materials, forming highly combustible, lighter hydrocarbons, hydrogen, methane and carbon dioxide. Given sufficient residence time an analogous gasification of carbonaceous materials will occur using supercritical water (Modell, 1978.)

Formation of carbonaceous char from less reactive carbonaceous materials such as coal is favored by short residence time, large particle size, and subcritical conditions (GA, 1997). High-carbon char has been produced by subcritical and supercritical water (Hawthorne, 1990).

Supercritical water shows promise in catalytic partial reforming of slurries made from refuse derived fuel, waste plastics, coal fines, and coal water fuels (Shaw, 1991). Data shows that fuel nitrogen will be converted to nitrogen gas (Sealock, 1996). Inorganic materials, such as sulfur, chlorine, alkali metals, ash, vanadium and other metals can be separated and removed for recycle or disposal. Activated carbon has been proposed as a catalyst for the conversion of biomass to hydrogen and methane in supercritical water. Unconverted carbon can be sequestered in char for decreased carbon dioxide emissions, or burned with additional coal in existing combustors.

If salts are present in the feed, or formed during processing, they will precipitate from solution wherever local temperatures exceed the critical temperature. Unless these solids are effectively transported through the supercritical region and effectively removed from the process, accumulations will form and plug the reactor tubes. Use of a commercial method of fluidized particle scrubbing using absorbent media has been proposed to prevent fouling and enhance heat transfer. The media can also be inert particles added to the feed or naturally present in the feed.

A commercial once-through HRSG tube bundle is shown in Fig. 4 with the inlet header. The tubes can be serpentine with extended external surface and over 100 ft. in length. Residence time can be controlled by the flow rate and the rate of heat transfer.

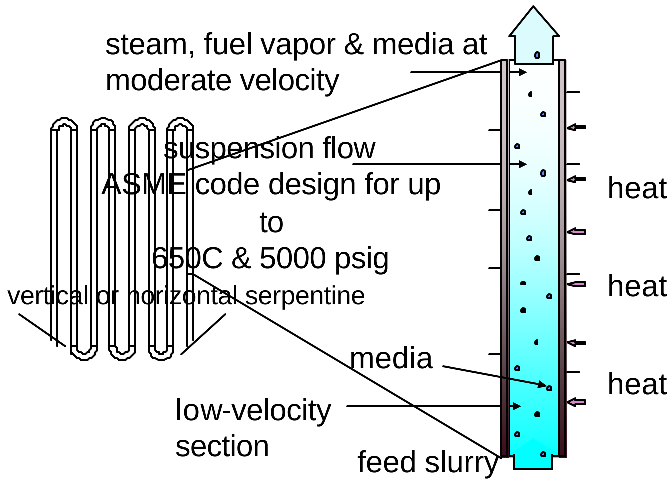

Fig. 3 Fluidized Transport Reactor Tube

Fig. 4 IST Once-Through Tube Bundle

Courtesy of Innovative Steam Technologies

Salts can be transported through the HRSG tubes by precipitating them on solid granular media in the system. Deposits can be minimized and heat transfer improved due to media impingement on the tube surface. Erosion can be minimized by using erosion and corrosion-resistant materials such as Alloy 800H in the heat transfer surface and by controlling slurry velocity.

Subsequent sections of this report describe the project approach, outcomes, conclusions, recommendations, and development stage assessment. Supplementary material includes a glossary, references and appendices. Appendix I is the General Atomics Test Report, and Appendix II contains additional information on SCWG and a description of the VTC.

Project Approach

In order to accomplish the Project Objectives, the project was organized into the following tasks:

Task 1 Bench-Scale Tests

General Atomics performed task 1 under the direction of Mr. Radon Tolman, Principal Investigator. The primary goal of Task 1 was to develop yield and quality data for applying supercritical conditions to convert compost to clean fuels on the bench-scale system. The results of these tests were used in the simulation modeling and cost and performance analysis of Tasks 3 and 4. In addition, the data will be used for the development and operation of the pilot plant.

The initial bench-scale equipment contained ¼ inch tubes with an inside diameter of .2 inches. These proved to be prone to plugging by large particles in the compost feed. The feed was ground to reduce particle size below about 500 microns. The small tubes in the bench-scale equipment were replaced by 3/8 inch tubes and some equipment was changed to lab-scale to more closely control the system. Details are included in Appendix I.

Task 2 Ultimate Analyses

Task 2 was performed by GA under the direction of the Principal Investigator. Analysis of the feed sample was to include proximate and ultimate analyses. Products were to be weighed. Gas and liquid products were to be analyzed to determine fuel values and to estimate further treatment that may be required to meet requirements for their use as fuels. Gases were to be analyzed for hydrogen, methane, light hydrocarbons, carbon dioxide, carbon monoxide and hydrogen sulfide. Liquid product were to be extracted with solvent to remove water and analyzed in a gas chromatograph for hydrocarbons, chlorine, sulfur, alkali metals, and total organic carbon.

Task 3 Incorporate Data in Simulation Model

Task 3 was performed by Dr. Jerry Parkinson, consultant, under the direction of the Principal Investigator. The process model was developed using existing subroutines where possible. The computer model is particularly useful for system optimization and will enable performance of economic evaluations based on both capital and operating costs associated with changes in operating conditions and/or system configuration. It will also enable determining the impacts of scale changes to both the design and the life-cycle costs of the process. The computer modeling effort began at the same time as the bench-scale experimentation and proceeded in cooperation with that work. This coordination was vital to ensure that all data necessary for the development of the simulation model are collected during the experimental runs. Other potential benefits of task coordination included use of the developing computer model to help validate the data collected (mass and energy balances, etc.), and to run sensitivity analyses for determining the most critical control parameters, which could help focus other work. The process simulation model will be continually refined and modified through input of pilot plant data.

Task 4 Feasibility Analyses

Task 4 was performed by the Principal Investigator with input from the consultant. Cost and performance analyses were to be prepared using the methods of the National Renewable Energy Laboratory, Golden, CO (Craig, 1996). The purpose of that study was to determine the efficiency and cost of electricity for IGCC systems incorporating biomass gasification technologies. The systems examined incorporate state-of-the-art commercially available aero-derivative and utility gas turbine technology and modern heat recovery steam cycle technology. It was clear from this study that even the most promising electricity costs from biomass were higher than currently quoted avoided costs and new high-efficiency natural gas fired combined cycle systems.

Preliminary capital and operating cost estimates were prepared for each alternative. Spreadsheets were prepared for comparing present values of the alternatives. The resulting comparisons indicate the commercial potential of the VTC system compared with published information for competitive systems, and define areas for continued and focused research in a pilot plant.

Task 5 Prepare Final Report

Task 5 was performed by the Principal Investigator. The results of Tasks 1 through 4 are presented in this report. Sensitivity analyses were to be prepared for variations in capital and operating costs associated with the uncertainties of the preliminary estimates and the risks associated with further research and development. A preliminary cost estimate and schedule for the pilot plant are included in this report, and incorporated in cumulative discounted cash flow projections for evaluation of the required research and development investments.

Details of the steps taken to achieve the stated goals, types of analyses performed on the data collected, and findings are included in the Appendices. Some conclusions from the testing are also included in Appendix I. Additional conclusions have resulted from the preliminary process modeling and feasibility analyses.

Project Outcomes

Use of SCWG to gasify composted municipal solid waste/sludge is feasible by a wide margin:

- We produced pumpable slurry mixture containing 40 wt% solids, exceeding the target goal by 74%.
- The bench-scale system converted over 98% of the carbon in the slurry to energetic gases and steam, including clean pressurized methane, hydrocarbons and carbon oxides in less than one minute, which is twice as fast as the target time.

The ultimate analysis for the compost used in the project was based on Bedminster data shown in Table 1. This analysis was assumed to be sufficiently representative of the cured compost before slurry preparation. Preparation of the slurry feed required grinding of the compost material to reduce particle size to avoid clogging in the tubes in the lab-scale system (See Appendix I). Testing is planned in a pilot plant to identify the optimum level of grinding required (if any) for trouble-free gasification.

Table 1. Ultimate Compost Analysis

Component	Weight Percent
Moisture, as received	18.7
Carbon	34.1
Hydrogen	3.3
Oxygen	19.2
Nitrogen	0.7
Sulfur	0.2
Chlorine	0.4
Ash	23.4

The gross heating value of the compost was calculated using Dulong's formula:

Higher Heating Value (HHV in Btu/lb) = 14096*C + 61,031*(H - O/8) + 3,984*S,

Where C,H,O and S are the weight fractions of carbon, hydrogen, oxygen and sulfur in the sample. The HHV for the dry compost was calculated as about 6,600 Btu/lb. The HHV of the 40% solids slurry was then about 2,640 Btu/lb. See Appendix II for a discussion of lower heating value (LHV) and the exergy of slurries.

A summary of test results follows:

- Through experimentation pumpable biomass slurry mixtures containing 40 wt.% solids were achieved which exceeded the target goal of 23 wt.% solids.
- The lab-scale heat recovery steam generator converted 98% of the carbon in the slurry to gases.
- Gases produced from composted sewage sludge and municipal waste:
    - 8-11% H_2
    - 16-17% CH_4
    - 7-12% CO

- 56% CO_2
- 6% Other

- The high concentration of CO_2 is a direct result of high oxygen content in the feed. All of the pressurized gases from SCWG can be used to produce electric power in the VTC expander turbine. However, excess CO_2 and steam may interfere with combustibility in the gas turbine combustor. This potential problem will be addressed in the pilot plant testing stage of development.

- Liquid effluent analysis:
  - 1350-2630 mg/kg total organic carbon
  - 7.66-7.81 pH
  - <0.01 mg/kg Cr
  - <0.04 mg/kg Ni
  - <1.52 mg/kg Fe
  - 93,000 mg/kg total suspended solids

- Total suspended solids in the liquid effluent was less than 10%, supporting the feasibility of recycling liquids for slurry preparation after filtering to provide zero liquid effluents. No toxic materials were produced that would limit disposal of the residue in a landfill.

- No noticeable erosion, corrosion or deposition was observed in the test equipment.

- A thermodynamic computer simulation model and a life cycle cost model were prepared and compared to an ASPEN simulation prepared for U.S Patent 5,280,701; however, there was insufficient funding in the current project to validate the models over a range of inputs, including the test data. Equilibrium compositions were assumed to be sufficiently close to expected commercial operations to provide preliminary predictions of system performance. Results of the computer simulations included:
  - Projected 62% thermal efficiency to electric power for a hybrid plant using a solid oxide fuel cell. Projected efficiency for application to an existing steam power plant is over 50%.
  - Projected capital costs of $1,100/kWh for a new hybrid plant, with projected cost of baseload power generation at $100/MWh.
  - Projected capital costs of $500/kWh for retrofit to an existing GTCC plant, with projected cost of baseload power generation at $50/MWh.
  - Retrofits for repowering existing boiler plants are competitive with GTCC plants burning natural gas at over $3.00/million Btu.

A computer-based process simulation model was prepared for a net 156 MW hybrid version of the VTC that includes material and energy balances. The heat and mass balance data were adjusted for 50 MW total output. Results predicted 62% HHV thermal efficiency to electric power using a supercritical steam turbine, a solid oxide fuel cell and a commercial gas turbine. The improved system appears to be patentable (See Appendix II).

Conclusions and Recommendations

This project resulted in the following conclusions:

- The test results support the continued investigation of composted municipal waste as an economical fuel source for GTCC and existing steam power plants.
- We demonstrated that compost made from municipal solid wastes and sewage sludge can be made into a slurry with 40 wt% solids, which significantly increases the range of applications, including the production of valuable byproducts, such as hydrogen. This mixture tended to clog in the ¼ inch preheater tube which was completely alleviated by changing to 3/8 inch tubing. This problem is not expected in larger tubes.
- The project successfully demonstrated that the compost slurry can be used in a SCWG process to produce energetic gases and steam, including approximately 35% gaseous hydrocarbons and hydrogen, the largest fraction being methane. The remaining 65% of the carbon in the feed was converted mainly to CO_2 and a small amount of CO. The CO_2 can be separated for reduced emissions. It is unknown what effect compost grinding had on residence time for gasification. It is also unknown what impact scaling up the reactor tubes will have on the SCWG process.
- Sufficient yield data was collected to determine gas composition, perform a carbon balance and perform a preliminary evaluation of recycling liquids after filtering for slurry preparation. While no corrosion, erosion or deposition was observed after running the tests, the tests conducted were not designed to fully assess those effects over the long-term under standard operating conditions.
- Environmentally, based on residence time and projected full scale HRSG tubes, a standard module of 100 HRSG tubes per 25 MW turbine can consume an estimated 170 tons of composted municipal solid waste per day, reducing it to approximately 34 tons of inorganic material.
- The results of the computer simulation models are encouraging in terms of supporting an economic case for commercialization; however, the models still include many assumptions that remain to be validated.

The next step is to assess the regime of slurry concentrations by conducting tests over the useful range using full-scale HRSG reactor tubes. The logical test bed would be the new SCWG research pilot plant being constructed at General Atomics in San Diego that is designed to test a wide range of SCWG applications. Additional funding is needed to conduct tests to determine the following:

- Identify the optimum concentration of slurry that can be successfully gasified in full size reactor tubes,
- Identify the optimum level of grinding required (if any) for trouble free gasification in full size reactor tubes,
- Confirm slurry distribution in a 10-tube inlet manifold for scaleup to a commercial plant,
- Confirm that the energy balance for SCWG is the same using full size reactor tubes,
- Evaluate the longer-term potential for corrosion, erosion or deposition,
- Test condensate for yield and quality and cleaning methods for recycle to slurry preparation,
- Test ash for beneficial use or land filling,
- Test mild operating conditions for byproduct yields and quality, including liquid hydrocarbons and carbon,

- Refine computer models and economic feasibility analyses for retrofit to existing gas turbines and boilers, and
- Collect and test fuel gases for combustibility in existing gas turbines, fuel cells and boilers.

By establishing the technical feasibility of the proposed SCWG concept, the project moves one step closer to making a significant contribution to the Public Interest Energy Research (PIER) program objective of improving energy cost of California electricity through the use of inexpensive biomass fuels. The project also has the potential to contribute to the PIER objective of mitigating environmental risks, including reducing emission of greenhouse gases and ground water contamination by removing biomass materials from the landfill and by diverting waste streams away from landfills.

The data generated in this project resulted in a projected increase in system efficiency of 10% for an existing steam power plant retrofitted with this technology. This increase derives from the current efficiencies of about 40% being improved to over 50% with this technology. Further, an increase in plant biomass consumption capacity of 220% was obtained over the previous best estimates. This percentage is based on the demonstrated increased percentage of solids in the slurry and shorter residence time required in the HRST tubes.

California is currently generating about 575 Mw from biomass sources (cited from California Biomass Energy Alliance). These plants use forestry, agricultural and urban wood wastes for fuel. With this technology we can add composted MSW, sewage sludge and green yard wastes. The city of San Diego alone generates 200,000 tons of these materials yearly. It is estimated that the major urban areas of California generate sufficient MSW and sewage sludge to support Ten 50 MW combined cycle power plants of the type proposed for a total capacity of 500 MWs. Requirements to increase the diversion of landfill waste streams and the increasing costs of natural gas further reduces the risks associated with commercialization. The lifecycle cost analysis targets fuel cost of the processed compost at about $1.00/Mbtu. This is based on the assumption that the tipping fees cover the majority of the cost of processing the biomass into compost.

Assuming the ten 50 MW combined cycle power plants were built and used for base load generation at 80% availability (7000 hours/year), they will produce 3,500,000 Mwh of electricity per year. Under current conditions this power could be sold on a long term contract at 7 to 8 cents/Kwh, resulting in revenues of $280,000,000 per year. Consider that the fuel cost savings of displacing natural gas at $5.00 Mbtu in this analysis results in fuel cost savings of about $100,000,000 / year.

Development Stage Assessment

Table 2 is a bar chart table describing the overall development effort in terms of the EISG Stages and Gates process.

Table 2. Project Development Stage Activity Matrix

Stages / Activity	1 Idea Generation	2 Technical & Market Analysis	3 Research	4 Technology Develop-ment	5 Product Develop-ment	6 Demon-stration	7 Market Transfor-mation	8 Commer-cialization
Marketing								
Engineering / Technical								
Legal/ Contractual								
Risk Assess/ Quality Plans								
Strategic								
Production. Readiness/								
Public Benefits/ Cost								

- Marketing
  Graduate students at the University of Colorado Business School prepared a preliminary Business Plan. This preliminary Plan is outdated and needs to be changed with a new title and improved schedules and costs to be determined in the proposed Stage 4 technology development project. Customer needs should be clarified as part of this process, including estimates of market potential for various applications of the technology. Potential commercializers should be contacted and interviewed for the Business Plan to provide feedback from existing customers as well as to identify additional customers and stakeholders.

- Engineering/Technical
  Performance goals have been set, as outlined in this report, including over 50% thermal efficiency for retrofit projects, power costs below $0.05/kWh, fuel cost reductions, minimum emissions and zero liquid effluents. A technical analysis should be prepared using a peer review process approved by the Commission. The product has met or exceeded the technical goals set for the project in Stage 3 and met the feasibility criteria.

  There is justification to proceed with the proposed Stage 4 development project with pilot plant testing before solving the remaining technical problems. The pilot plant is the only source of sufficient equipment, instrumentation, capacity and capabilities to solve the remaining technical problems. A Test Plan for the pilot plant and subsequent field experiments should be developed to direct data acquisition and analysis that support the proposed process and economic models.

  - Legal/Contractual
    U.S. Patents 5,280,701 and 5,339,621 have already been issued. Development of additional intellectual property, including improvements and information related to specific

applications is anticipated. Proprietary information, including intellectual property, will be protected in accordance with best business practices and Commission requirements. No other legal patents issues have arisen at this time.

Identified commercializers will be asked to submit existing and projected sales data as part of the process for selecting a commercializer for this technology.

- Risk Assessment/Quality Plans
  A Quality Plan needs to be developed that meets ISO 9004 Quality Management and ISO 9001 Quality Assurance criteria. The Quality Plan will specify quality control criteria, including technical performance, safety and environmental performance, in accordance with ASME, AWS, ASTM, IEEE standards, California and federal regulations. Selected elements of the Quality Plan will minimize risks by applying risk reduction techniques with safety analysis methods.

  Environmental and safety issues include measurement and prediction of any emissions based on pilot plant results, continuous emissions monitoring, zero liquid effluents, residue disposal and licensing. These issues will be resolved during the proposed Stage 4 development project so that Gate 4 criteria will be met.

  A life cycle analysis is proposed to be performed early in the pilot plant step of Stage 4 development to support life cycle cost analyses and predictive maintenance costs for the Business Plan. No new risks have been identified at this time. Any new risks that result from the proposed Stage 4 pilot plant testing will be identified and reported in accordance with Commission requirements in close collaboration with PIER staff.

- Strategic
  Development of the technology has been linked to PIER policy objectives. This project does not appear to impact other PIER projects at this time. This project is not critically dependent on other projects under development within PIER or elsewhere.

- Production Readiness
  A research and development collaborator has been identified in General Atomics in San Diego. Top candidates for commercializing partner remain to be identified and interviewed in support of product marketing and the revised Business Plan to fulfill legal and contractual requirements described above. The selected commercialization partner should submit evidence of a firm commitment based on successful completion of Stage 4 tasks and meeting the criteria for Gate 4 product development and field testing in Stage 5.

- Public Benefits/Costs
  The empirical data generated in this project resulted in a significant increase to the calculated California public benefit-cost ratio. Project results support continued concept development for retrofits to existing natural gas fired boilers and combined cycle plants. The benefits to be derived from substituting biomass fuels for higher-cost fuels, including more expensive natural gas has improved since this project was completed.

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