

# **HAWAII'S FUTURE WITH INTEGRATED GASIFICATION FUEL CELL COMBINED CYCLE**

Prepared for Tom Sullivan

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## **1. EXECUTIVE SUMMARY:**

Hawaii has several serious problems:, (1) Hawaii very much needs to replace petroleum imports that now account for more than 85% of its' energy requirements and up to 20% of all state imports, (2) the State agricultural industry is currently surviving on subsidies and the promise of a viable biomass-to-energy scheme will help dramatically, (3) the disposal of waste streams without use of landfills and without incineration of the waste and (4) the State energy production infrastructure is a major polluter. This project focuses on using locally generated municipal solid waste (MSW) as well as agricultural waste in a new process involving steam and carbon dioxide reformation to make clean energy as well as transportation fuels.

In this design study, a commercial indirectly heated rotary kiln reformer was used to process MSW and bagasse and other biomass using steam and carbon dioxide (CO<sub>2</sub>) from the process to produce the hydrogen-rich syngas to drive fuel cells to make high-efficiency electricity as well as use some of the syngas to synthesize clean transportation fuels. The plant was sized at 50,000 tons/year fed by MSW with a tipping fee of \$30/ton and either coal or bagasse and other biomass costing \$40/ton. The plant produced 14 MWe of premium, uninterrupted electricity as well as 250 bbl/day of middle distillate that was low in sulfur and high in cetane (i.e. high octane).

The plant's schematic process sheet was prepared and each of the major pieces of equipment were sized and costed. The process controls were envisioned that allowed automatic operation with the lowest manpower needs. The operations and maintenance costs were then estimated. These data were used to prepare a large economic model for the plant performance. First, it was found that bagasse and other biomass had advantages over coal, in addition to greatly reducing the need to import foreign coal to Hawaii. Two cents/pound will be paid to suppliers of coal or bagasse or other biomass which will be offset by income of 1.5 cents/pound for a "tipping fee" collected for disposing of MSW. The largest income streams came from premium power electricity sold, middle distillates and recyclables of glass and metal recovered. There were also savings against present practice through green credits and CO<sub>2</sub> reduction credits. The economic model showed a 5.81 year payback and an ROI of 17%. Also by reducing the oil dependency by a factor of 2:1, there will be economic benefits beyond the plant itself. This positive analysis suggests that such an energy plant using MSW and biomass be considered in Hawaii.

## 2. The Chemistry of Steam/CO<sub>2</sub> Reforming

FIG. 1 is a plot of the commercial steam reforming of methane that is a well known commercial process and is the principal process for manufacturing hydrogen gas in refineries for use in petroleum hydro-cracking and hydro-reforming process steps as well as manufacturing hydrogen gas as a commodity sold in the marketplace. Standard nickel catalysts are used for this conversion in order to lower the reactor tube temperatures so that less expensive alloys can be used and their process lifetime extended.

First, some explanation of these computed results is helpful. The calculations are performed by the method of Gibbs Free Energy Minimization to yield gas compositions at thermodynamic equilibrium from the lowest temperature of 200°C up to 2000°C. The chemistry is started by placing methane (CH<sub>4</sub>) and steam (H<sub>2</sub>O) at one atmosphere in the gaseous (subscript, g) state in a vessel at 200°C. We wait for a very long time for the compounds to react slightly and form a small quantity of hydrogen (H<sub>2</sub>) and carbon dioxide (CO<sub>2</sub>). This composition of the gas mixture is that which occurs if the chemical kinetics were fast enough to allow the reaction to reach completion in the time allotted. There are actually two reactions that are occurring simultaneously here:



As soon as the H<sub>2</sub> and CO<sub>2</sub> are formed, the “Water gas shift reaction” forms H<sub>2</sub>O and CO by:



In this way, the two reactions interact according to each of their free energy driving forces to arrive at an equilibrium balance, and the final compositions are shown in the FIG. 1. As the temperature is raised, the equilibrium shifts to forming H<sub>2</sub> and CO.

Practically speaking; however, commercially one cannot wait long periods of time for the slow chemical kinetics at 200°C to reach the equilibrium composition. The gas composition curves are achieved more quickly with less residence time when active surface catalysts are used to impart extra energy into the gases to encourage them to react more quickly. As the temperature is increased, the kinetic velocities and energies are increased by the increased kinetic activities of the gases carrying more energy in their collisions and forming other compounds more quickly. Eventually, as the temperature is increased significantly to say 600°C, the kinetics become so fast that no active surface catalyst is needed. Thus, the gas compositions shown in FIG. 1 can be achieved at temperatures above 600°C without the use of catalysts since the approach to thermodynamic equilibrium can be achieved in reasonable residence times. To make commercial H<sub>2</sub>, the commercial embodiment carries out the gas-phase chemistry inside of catalyst-coated tubes or tubes filled with catalyst-coated ceramic beads. These tubes are heated externally by means of very hot flue gas from a gas-fired furnace, sometimes using oxygen-enriched combustion air.

We also need to make sure that the chemistry produces a practical ratio of H<sub>2</sub>/CO in the syngas which is used in the Fischer-Tropsch gas-to-liquids plant that can produce a range of useful commercial products, such as middle distillates as a valuable transportation fuel or low sulfur and high cetane blending stock for refineries.

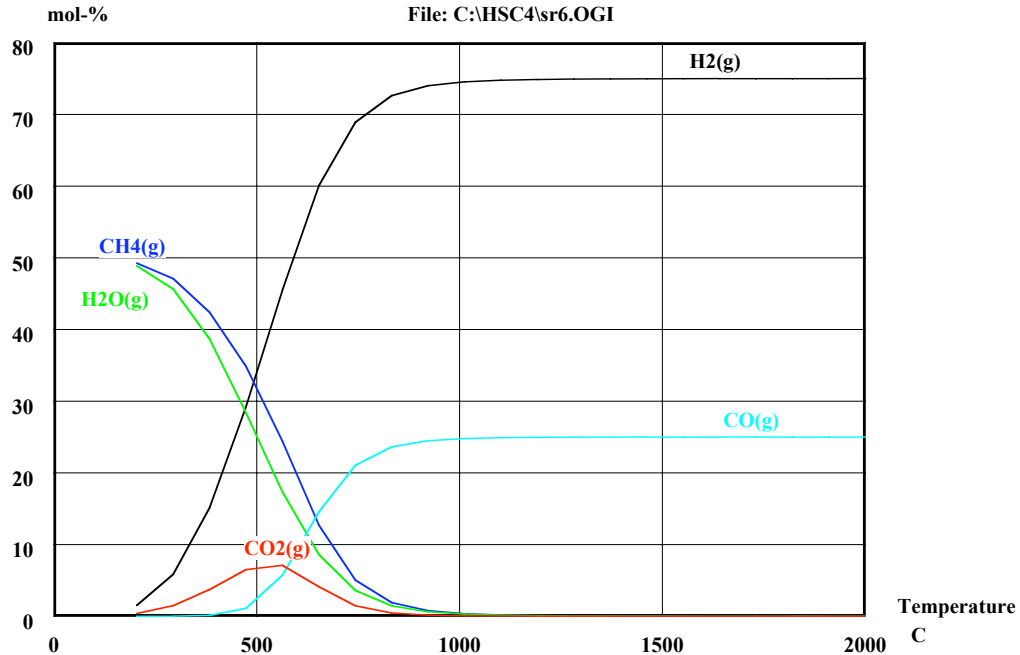


FIG. 1 is a plot of the commercial steam reforming of methane to make syngas consisting of hydrogen and carbon monoxide. (sr6)

As the molecular complexity of the feed hydrocarbons increase, the temperatures have to be increased to levels well above 600°C in order to approach their chemical thermodynamic equilibrium composition without the enhancing and accelerating effect of catalysts. In fact, we find that above 700°C is practically where catalysts are no longer needed when dealing with organic wastes [1-10].

Commercial gasification processes for coal, coke, petroleum, organic waste, etc. use high pressure, entrained flow, and partial oxidation, such as the Texaco Gasifier or the Shell gasification process [4-5]. These large gasification reactors operate at low enough temperatures that more cost-effective alloys can be used at high pressures for these commercial gasification vessels. When low pressure gasification catalytic beds are often used, for temperatures of 700°C and below, the wastes must be carefully selected so the catalysts are not easily poisoned when waste is used as feedstock, because of halogen and heavy metal contaminants in the MSW. But a better solution is to work at higher temperatures without catalysts and avoid this problem of wastes and catalyst poisoning.

Now introducing high temperature fuel cells [11-19] into the process, FIG. 2 shows the steam/CO<sub>2</sub> reforming of a mixture of methane (green curve) and fuel cell-produced carbon dioxide added into the feed at 20%. Again at high temperatures over 700°C, the syngas compositions shown are achieved without the need for catalysts. Comparing FIG. 1 and FIG. 2 beyond 800°C, it is noted that the hydrogen content is slightly lowered by the presence of increased carbon monoxide and water that are formed and by the residual carbon dioxide, since all three act as significant diluents in the formed syngas product, diluting the hydrogen. In fact, the carbon dioxide has two positive effects in the reaction: (1) it is consumed so that it is not released to the environment and (2) it lowers the H<sub>2</sub>/CO so the syngas is better handled in the Gas-to-Liquids plant making middle distillates.

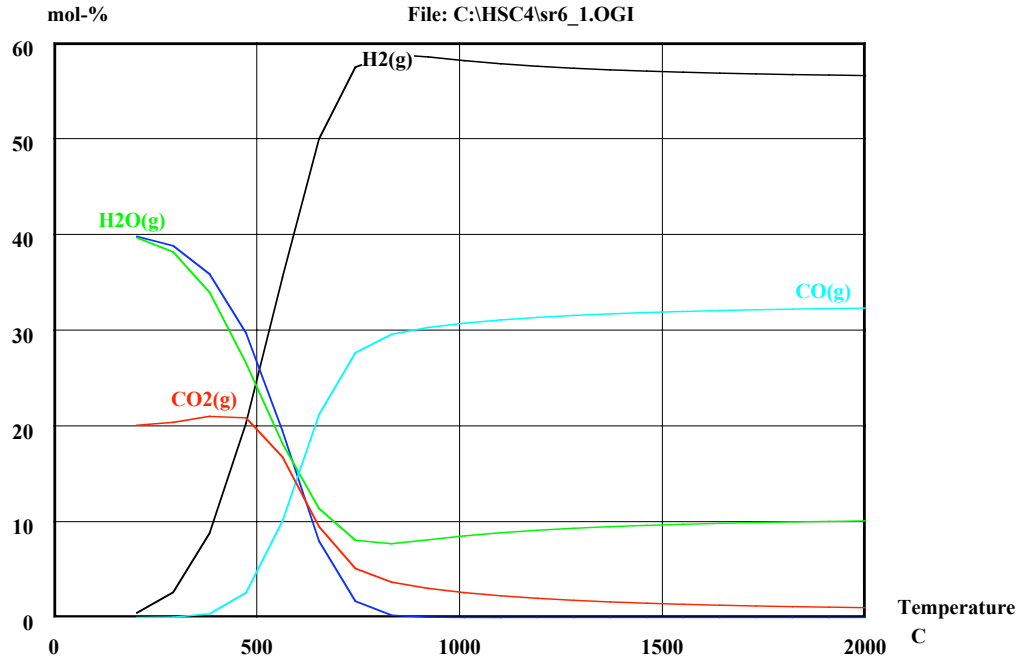
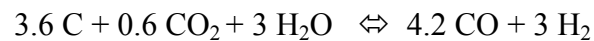


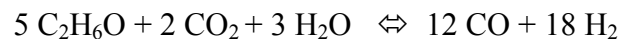
FIG. 2 shows a plot of the steam reforming of a mixture methane and fuel cell produced carbon dioxide at 20% in the feed. (sr6\_1)

But surprisingly, once departing from conventional past thinking, there is a much-preferred solution to optimize this fuel cell link that has been overlooked and not exploited previously. It involves using elevated steam feed and CO<sub>2</sub> simultaneously with complex waste streams that have higher carbon/hydrogen ratios than simple methane. This approach appears at first to be contrary to common thinking and conventional practice, that suggests that to achieve optimum hydrogen concentrations at high temperature, the worst option is to INCREASE the carbon content of the feed. But this simplistic logic is, in fact, very wrong, as shown here and in our patent filings.

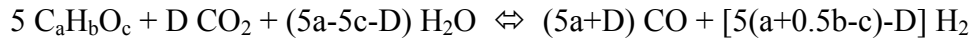
Consider the very simplified chemical reaction with the waste stream fairly characterized entirely by carbon:



This is already 40.5% by volume hydrogen (i.e. mole percent). This is the rough optimum, maximizing hydrogen content. Varying the stoichiometric quantities of the reactants produces less than optimum hydrogen, but maintains as constant syngas mole volume, which is a very desirable end result. Note, that the addition of CO<sub>2</sub> reduces the requirements for water below stoichiometric requirements. In fact, there is an optimum combination of using both CO<sub>2</sub> and water in achieving target H<sub>2</sub>/CO ratios, while maintaining high levels of syngas product. A MSW example might be:



A generalized chemical reaction can be written for most carbonaceous feedstocks as expressed by the generalized empirical formula,  $C_aH_bO_c$ :



The  $H_2/CO$  ratio can be optimized by the right combination of  $CO_2$  &  $H_2O$  for a given waste feed mixture characterized by the empirical formula,  $C_aH_bO_c$ . Note, that the amount of  $H_2O$  needed is reduced below its stoichiometric requirements ( $5a-5c$ ) for conventional steam reforming by the “D” amount of  $CO_2$  needed, since the stoichiometric coefficient on  $H_2O$  is now ( $5a-5c-D$ ).

Also, to help us adjust the  $H_2/CO$  ratio needed for Fischer-Tropsch synthesis of useful chemical co-products to sequester the carbon and avoid greenhouse gas emissions, examining this  $H_2/CO$  ratio is helpful, since it is expressed as:

$$\frac{H_2}{CO} = \frac{5(a + 0.5b - c) - D}{5a + D}$$

Note, for a given carbonaceous feedstock with the empirical formula,  $C_aH_bO_c$  one can adjust the amount of  $CO_2$ , “D”, to satisfy the Fischer-Tropsch synthesis requirements.

To achieve higher hydrogen concentrations at high temperature to drive the fuel cells, increased feedstock hydrogen content together with an excess steam below stoichiometric levels, ( $5a-5c-D$ ), is allowed, combined with the recycled fuel cell carbon dioxide, D. This provides the chemistry at thermodynamic equilibrium that achieves a higher hydrogen-rich syngas that remains high and steady in hydrogen over a broad high temperature range up to and beyond  $1300^\circ C$  without catalysts.

FIG. 3 shows a plot of the steam reforming of a mixture of a typical industrial solvent waste (acetone, formaldehyde, methanol, dimethylbenzene, butanol, trichlor, and perchlor). Even further improvements can be made, surprisingly, by increasing the recycle  $CO_2/H_2O$  ratio from the 0.0 in up to 0.5. This added  $CO_2$  was from the fuel cell. The steam used in FIG. 3 is actually a DECREASE to 60% in the amount of steam consumption in the process, with the advantage of the steam/ $CO_2$  reforming reactor being able to accept more  $CO_2$ , contrary to conventional thinking.

This example shown represents well the case of MSW and Bagasse and other biomass streams as described in the MSW stoichiometric reaction given above. One amazing result of high temperature processes is that the final gas composition is determined entirely by the atomic mix of the waste being fed into the process and not the molecular species. In fact, the final syngas composition is dominated by carbon, hydrogen, oxygen as the major constituents. In MSW and Bagasse and other biomass, there is also nitrogen, which under this reductive chemistry produces ammonia that neutralizes any acid gases produced such as hydrogen sulfide from any sulfur in the waste. If further neutralization is needed in the plant, lime is typically added into the rotary kiln, where in the fine particular state it immediately reacts with any acid gases produced. These acid gases are neutralized to form harmless salts that drop out with the solids at the exit of the kiln.

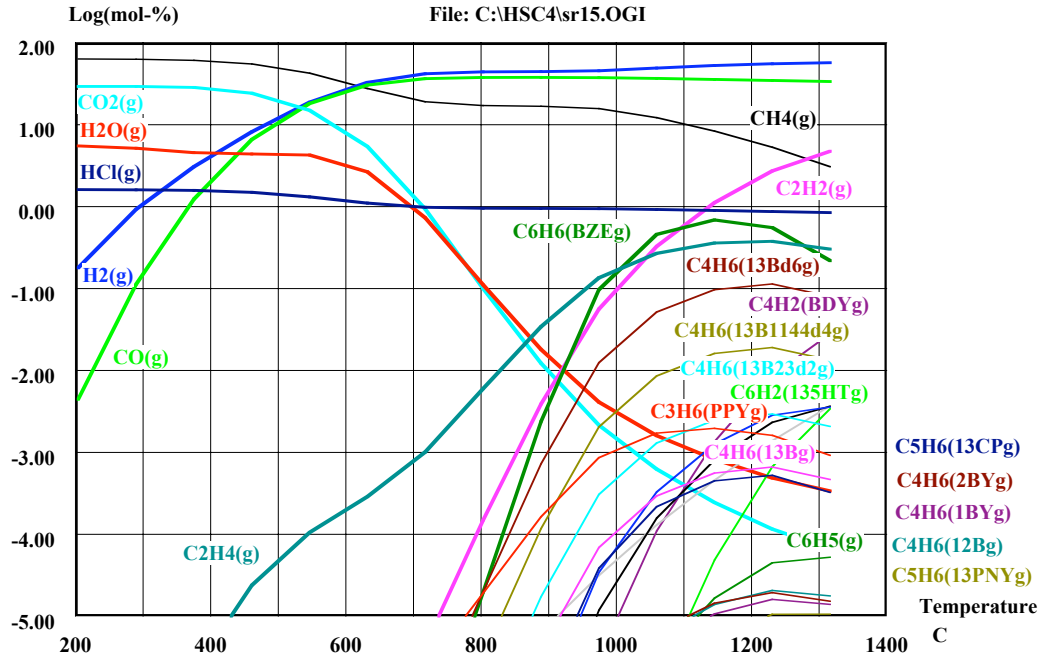


FIG. 3 shows a plot of the steam/ $\text{CO}_2$  reforming of a mixture of typical industrial waste, no fuel cell-produced  $\text{CO}_2$  added in the feed with super-stoichiometric steam at 60% achieving high hydrogen but dirty syngas. (sr15)

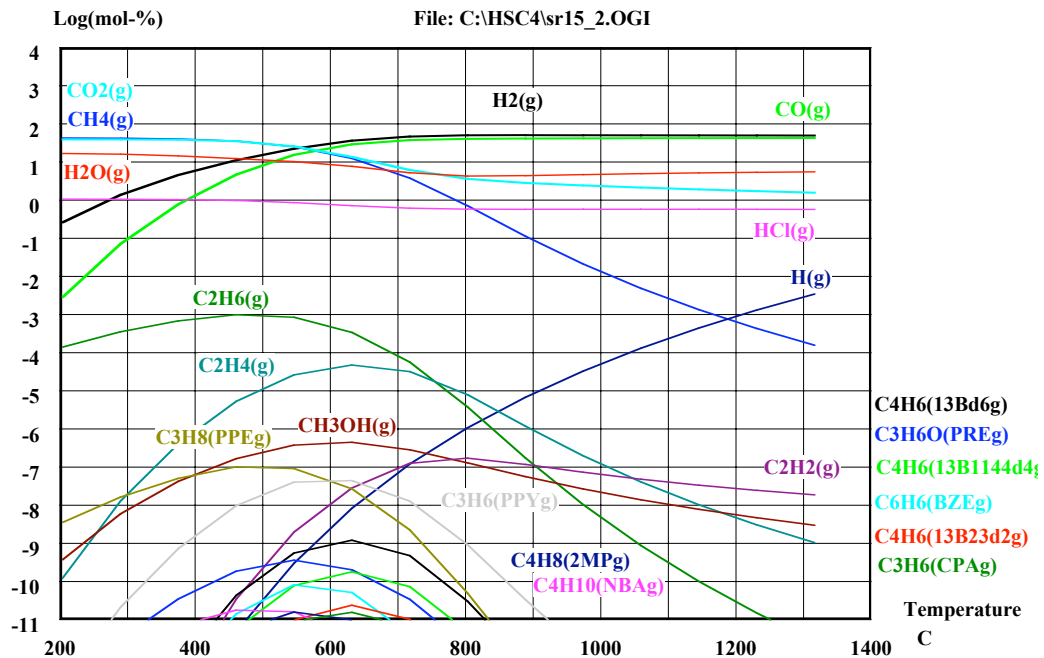


FIG. 4 Steam/ $\text{CO}_2$  reforming a mixture of a typical industrial waste and fuel cell produced carbon dioxide at 20% added in the feed with super-stoichiometric steam at 60% achieving high hydrogen and the cleanest syngas. (sr15\_2)

Looking at FIG. 4 at 700°C or 1200°F, the syngas product composition starts at the highest with H<sub>2</sub>, hydrogen, at 50.0%; then CO, carbon monoxide at 42.4%; H<sub>2</sub>O, water at 5.36%; CO<sub>2</sub>, carbon dioxide at 1.73%; HCl, hydrogen chloride gas at 0.57% ppm; •H, hydrogen radical at 13 ppm; CH<sub>4</sub>, methane at 4.31 ppm; C<sub>2</sub>H<sub>2</sub>, acetylene at 24 ppb; C<sub>2</sub>H<sub>4</sub>, ethylene at 3 ppb; with all other compounds at levels below 0.05 ppb. Note: this is about 10 million times cleaner or lower in minor contaminants than in FIG. 3.

Both of these improvements are economically attractive commercially. This yields a H<sub>2</sub>/CO around 1.18, that is a syngas composition more amenable to making more valuable chemical co-products than methanol (selling only @ 50¢/lb), such as middle distillates, for example, that requires a H<sub>2</sub>/CO of 2.0 for its synthesis. Thus, the addition of shift reactors to adjust the H<sub>2</sub>/CO upward or downward are not required – a further economic advantage of this new process. The advantage of the current method is that by recycling CO<sub>2</sub> and adjusting the levels of CO<sub>2</sub> versus H<sub>2</sub>O, an optimum H<sub>2</sub>/CO ratio from about 1.0 to about 1.5 can readily be achieved to match the end products required for either the Fuel Cell or Gas to Liquid conversions and equally as important to achieve the ever-elusive sequestering of near 100% of the greenhouse gas, CO<sub>2</sub>. The process equipment designed to accomplish this chemistry most economically is a slightly inclined horizontal rotary kiln that is heated externally. These are called “indirectly heated rotary kilns.” See FIG. 5.

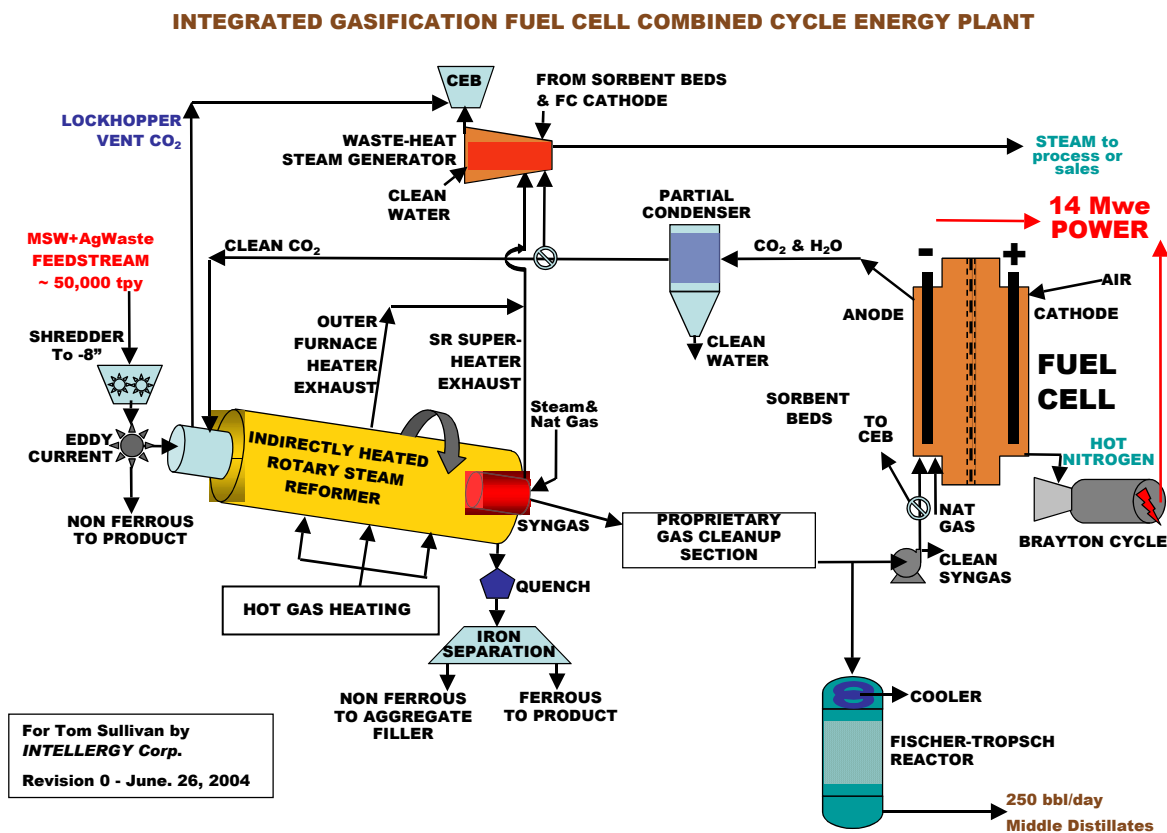


FIG. 5 Shows the indirectly fired steam/CO<sub>2</sub> rotary kiln and its interface to the fuel cell.



The slight inclination encourages the feedstock to move axially along the rotary kiln away from the feed end as it is rotated slowly. The carbonaceous feedstock or waste near room temperature is introduced into one end wherein the kiln temperature may be at 400°C, and it is subjected to increasing temperatures as it moves along the kiln toward the exit end that would be preferably around 900 to 1200°C. The higher temperatures would be needed to accomplish the high levels of destruction required by U.S. EPA law should there be listed hazardous waste contaminants in the waste feedstock. For recovery of metals and glass for possible recycling, these solids would be removed from the kiln before they are melted. Such a conceptual drawing of this contemplated waste feed section to the rotary kiln is shown in FIG. 5. This is a slightly inclined rotary kiln where the residual solids are removed at the solids exit from the rotary kiln as the location in kiln reaches about 400°C along its length before they are melted there is a slipstream portion of the syngas that feeds the Fischer Tropsch synthesis unit producing the carbon-containing chemical co-product.

In this plant, the CO<sub>2</sub> produced from the anode of the fuel cell is recycled back into the reformer so that it can be part of the steam/CO<sub>2</sub> reforming chemistry to produce added syngas to synthesize middle distillate as the product which is sold. In this way, the carbon in the MSW is sequestered and not released into the atmosphere to add to the greenhouse gas problem. FIG. 6 shows how the carbon balance works so that all the carbon going in as part of the waste feed leaves the process as a sequestered carbon-containing co-product for sales. These products are selected from a list of products that are never burned during their life cycle in order to insure carbon sequestering forever.

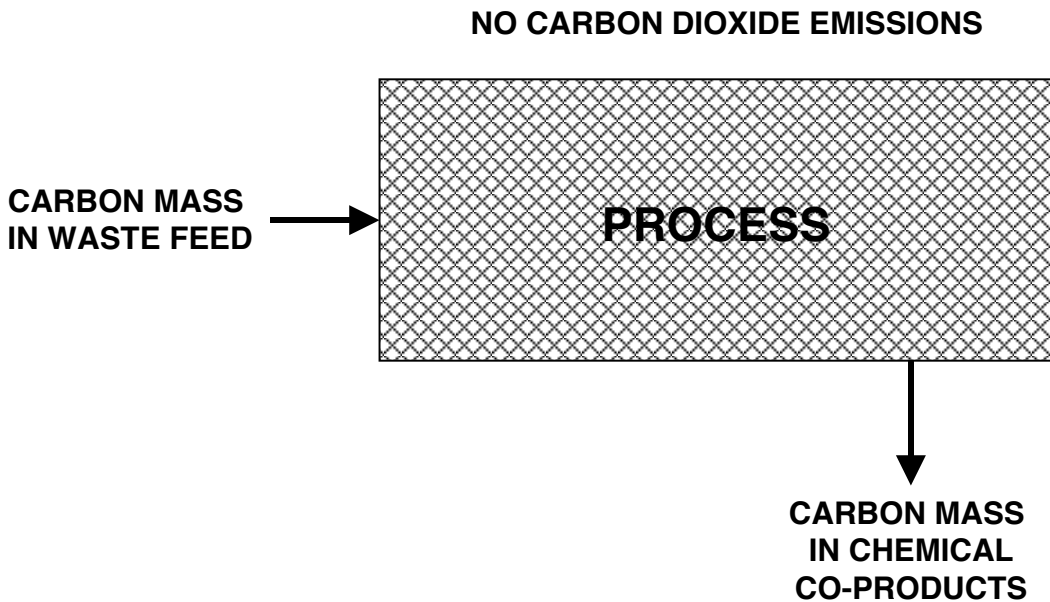


FIG. 6. Carbon balance.

### 3. Lab-Scale MSW Steam/CO<sub>2</sub> Reforming Rotary Kiln Test

The purpose of the laboratory-scale rotary kiln proof-of-principal test was to show that a representative sample of MSW could be steam/CO<sub>2</sub> reformed in rotary kiln to achieve a 90% volume reduction with a practically short residence time.

The MSW was sampled to obtain a surrogate sample representative of Hamilton, Ont. This MSW surrogate was submitted to a thermo-gravimetric analysis that showed an 80% mass loss in 80 minutes at 650°C (1200°F). From the shape of this curve, it could be concluded that at a slightly higher temperature and longer times, 90% mass reduction could be obtained. These tests were performed under a research contract with Shaw Environmental and Infrastructure of Knoxville, TN.

This surrogate was also subjected to Ultimate Analysis that showed on a weight basis: Carbon=47.90%, Hydrogen=6.67%, Nitrogen=2.89%, Sulfur=0.29%, Chlorine=1.62, Oxygen=30.12%, Ash=4.28%, Inerts=6.24%. The Proximate analysis showed 83.14% volatile matter, Ash=4.28%, fixed Carbon=12.28%. These tests were done by Galbraith Laboratories Inc, of Knoxville, TN.

A size-reduced (about 1 cm size pieces) surrogate sample representative of Hamilton, Ont. MSW of 230 gms in mass was placed into the lab-scale (15 cm diameter x 40 cm long) rotary kiln heated section. An image of the raw sample is shown in FIG 7.



FIG. 7 Raw sample is shown

The tube was radiantly heated to 900°C, and subjected to a flow of superheated steam produced from 6 cc/min of water to the superheater, and 1 liter/min of carbon dioxide gas. The tube was rotated at 5 rpm and contained two lengths of 6.3 mm rebar tumbled with the MSW sample to simulate the frictional effects of a much deeper bed in the large commercial kiln. FIG. 8 shows this heated section of the lab rotary kiln about to be surrounded with the clam-shell furnace half-sections.

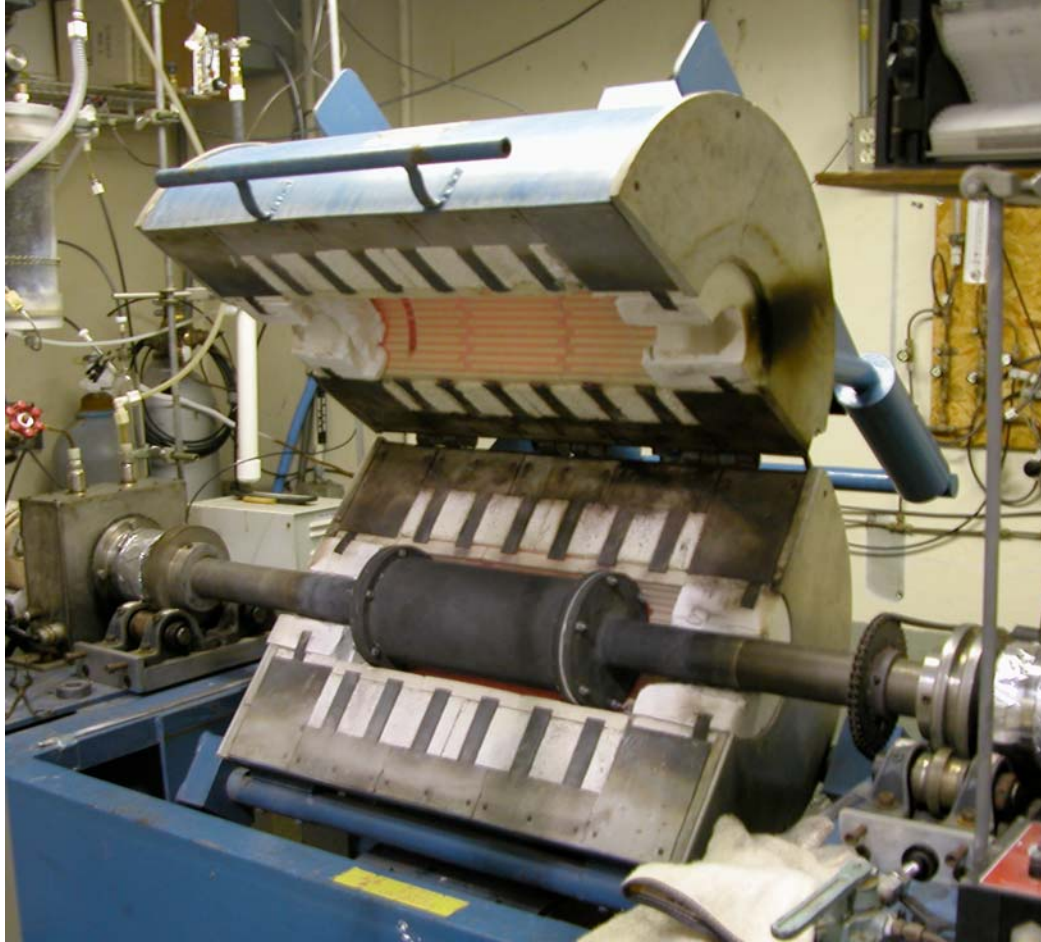


FIG. 8 Shows this heated section of the lab rotary kiln about to be surrounded with the clam-shell furnace half-sections. Sample is batch-loaded in large tube.

The test began at 11:05 am EDT where the room temperature tube was first subjected to radiant heating. By 11:27 am the tube reached 650°C with the steam/CO<sub>2</sub> reforming chemistry well started. By 11:50 am the syngas reached about 40vol% H<sub>2</sub>, 7.5% CO and 5% CH<sub>4</sub>. By 12:08 pm the 900°C setpoint was reached, at which point the remaining portion of the test continued. The CO was used as an indicator of the progress of the steam/CO<sub>2</sub> reforming conversion of the MSW. At about 50 minutes into the test, the CO had begun to peak at over 25%, and at 75 minutes reached 28%, and thereafter started its decline to the end of the test. The predetermined criteria for completion of the test was the exit CO declining to 5% (i.e. 1.4 % CO) of the peak reading or 2 hours at 900°C, as the carbon in the batch sample becomes depleted. At 120 minutes into the test (65 minutes at 900°C), the CO had dropped to 4.25% and by 193 minutes (130 minutes after reaching 900°C), CO fell below 1.4 % as read on the on-line monitor. At this point a Tedlar bag sample was taken to obtain the gas chromatograph confirmation. By 197 minutes (134 minutes after reaching 900°C), the GC showed 0.3% CO, well below the 1.4% cutoff point desired; so the test was stopped. FIG. 12 shows the clam-shell furnace halves opened and put away and the central tube glowing cherry red as it began its air cooling. After some time allowed for air cooling, the entry and exit tubes were water cooled and eventually (around 2:43 pm) the tube was opened to collect the final residue and determine its weight at 28.3 gms and density at 0.8 gm/cc, non-compacted.



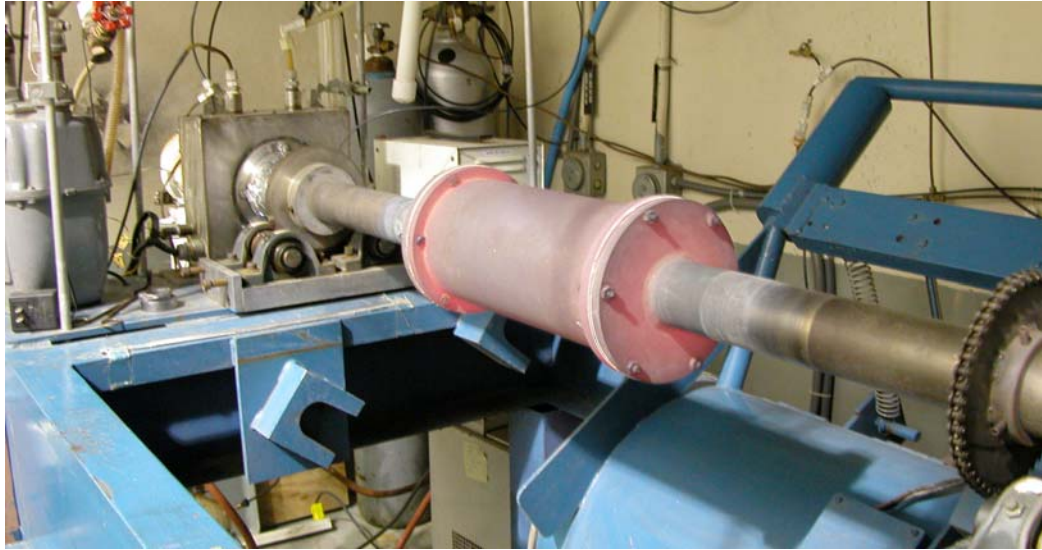


FIG. 9 Shows the clam-shell furnace halves opened and put away and the central tube glowing cherry red as it began its air cooling

The volume and mass reduction from the MSW initial volume of 2.4 liters (density = 0.096 gm/cc) non-compacted was calculated to be 98.5% volume reduction (VR) or 87.8% mass reduction (MR). Thus, we find the VR of 90% was achieved and the test was successful. Some compacting tests will change this VR value somewhat, but will be well over the 90% VR. FIG 10 shows the vial containing the final residue product. Note that it is a fine powder with no indication of the black hollow skeletal remains commonly called “Pyrochar,” indicating completion of the reaction. Note that the color is a mousey grey, also indicating the absence of residual fixed carbon remains. The final residue consists mostly of the inorganic fraction, comprising almost entirely the mineral kitty litter sorbent in the original waste feed.



FIG. 10 Shows the vial containing the final residue

The successful result of this proof-of-principle test showed that steam/CO<sub>2</sub> reforming using added CO<sub>2</sub> but less than molar excess superheated steam can achieve the desired VR and MR in a reasonable residence time. The steam/CO<sub>2</sub> reforming reactions were definitely past completion at the end of the test indicating that there may be room to either decrease the temperature from 900°C or reduce the retention time from 134 minutes or both. Further test work is planned to decrease operating design criteria below 900°C and 2.25 hours.

#### **4. Proforma Economic Analysis**

Using the above-demonstrated pilot-scale results, a feasibility analysis was done, costing all the capital in FIG. 5, process control, maintenance, labor requirement, and cost of money. There was tabulated all of the major process units, their costs, installation costs, etc.

Based on these data, a 50,000 ton/year steam/CO<sub>2</sub> reforming small-scale plant was scoped with the syngas feeding the fuel cell. The process controls were envisioned that allowed automatic operation with the lowest manpower needs. These data were used to prepare a large economic model for the plant performance. The operations and maintenance costs were then estimated. The plant is to be financed by a 5.5% municipal bond.

The economic model prepared from these data is proprietary. A full range of options were explored in this model to determine the optimum plant configuration.

As a direct replacement for Hawaii's foreign petroleum requirement, coal from Australia and/or Indonesia is available for about \$40 per ton delivered to any island with suitable harbor facilities. It will be mixed with local MSW until sufficient quantities of locally produced biomass are available at a comparable price that can replace all or part of it. To the extent that that happens, the system will be CO<sub>2</sub> neutral. That is, CO<sub>2</sub> released into the atmosphere by burning the middle distillates as Hawaii's transportation fuel that are produced by this process using biomass and MSW will be offset by the CO<sub>2</sub> captured as the biomass used in this process grows. Until that occurs, the benefit will be the ability to use coal as a viable alternative to imported oil in a process that is twice as efficient at existing facilities and creates virtually no pollution while producing its' electrical energy component. A plant closer to the size of the coal plant now operating on Oahu would consume 2,160 tons per day of coal or equivalent biomass and produce 163 MWe of electricity plus 8,250 barrels per day of low sulfur distillate worth \$346,500 at \$42 per barrel. That would be \$114 million in a 330 day production year that does not have to be imported, and, since the process produces oil rather than consumes it, the value of the oil not imported to produce 163 MWe also flows directly to the bottom line of Hawaii's trade balance. A complete replacement of oil burning energy plants will actually lower the states net fuel requirement due to the higher efficiency. The plant featured in this report is intended to be an example only. Each island can develop different ways to incorporate it into their energy future, and those choices will be local ones.

The overriding objective, of course, will be to produce crops or crop byproducts that can profitably be sold for \$40/ton to compete with imported coal. A new lumber-furniture industry, for instance, may sell wood scraps to the closest plant. There will be many new opportunities that will develop, but it will be unique in each application.

Once hydrogen vehicles become available, the process can avoid obsolescence by simply shifting its

production mix to hydrogen to meet those new requirements. It will be at that point that all of the CO<sub>2</sub> will be sequestered and true progress made against global warming. Chemical feedstocks for existing and new local industries would also be produced. There will still be a balance of trade benefit from the use of as much locally produced biomass as possible, however, as well as significant reduction in the amounts of greenhouse gas generated in mining and transporting coal to Hawaii.

Our processing technology using a large kiln avoids the feed problems experienced in past efforts at gasifying bagasse in Hawaii. As it was fed into the past gasifier in Maui, it would clog as the clumps got bigger, which occurred as the pile compacted over the course of the year. The rotary kiln used in our process is about 4 to 5 feet in diameter and capable of accepting huge clumps of biomass. This material enters the kiln through a large lockhopper which handles these large size clumps without shredding or serious size reduction.

In the economic model examined, the largest income streams came from premium power electricity sold, middle distillates and recyclables of glass and metal recovered. There were also savings against present practice, green credits and CO<sub>2</sub> reduction credits. The initial look [20-24] at the economics suggests an attractive 5-year payback for the plant can be achieved. The economic model showed a 5.81 year payback and an ROI of 17%. This positive analysis suggests that such an energy-from-waste plant be considered in Hawaii.

Using this economic model above, we also did a parametric study in which all variables except electricity were frozen. The price for the middle distillates sold was fixed at \$42/bbl, coal or biomass purchased was fixed at \$40/ton, and the plant breakeven point was calculated for electricity for three basic feed options: all MSW feed, 50% MSW and 50% coal/biomass; and all coal/biomass, ranked in this order – a very promising result.

## 5. References

1. T. R. Galloway, S. Depetris, "On-site Bio-hazardous Waste Destruction with the Synthetica Steam Detoxifier Test Organism Kill and Chlorocarbon Destruction," AIChE Annual 1994 Meeting, San Francisco, CA, November, 1994.
2. T. R. Galloway, Matt Cage, & Tom Snyder, Chapter 4.3 of "Hazardous and Radioactive Waste Treatment Technologies Handbook," entitled "Application of Steam-Reforming to Various Types of Radioactive Waste," CRC Press, Boca Raton, FL, July 2001.
3. T. R. Galloway, Matt Cage, & Tom Snyder, "Experience with Duratek Steam-Reforming of Various Types of Radwaste" April 2001.
4. T. R. Galloway, Joe Waidl, Cheryl Heath, and Lynn Ratcliff " Commercial Applications of Fuel Cells at Billings," U.S Department of Energy Project, Big Sky Economic Development Authority, Billings, MT , September, 2000
5. T. R. Galloway & Joe Waidl, " Partial Demo of Repowering of the Corette Plant with a Gasifier and Fuel Cell Combined Cycle," U.S Department of Energy Project, Big Sky Economic Development Authority, Billings, MT , July 28-31, 2000
6. T. R. Galloway, "Partial Demo of Repowering of the Corette Plant with a Gasifier and Fuel Cell Combined Cycle," U.S Department of Energy National Energy Technology Laboratory, Morgantown, KY, Feb. 24, 2000
7. T. R. Galloway, "Clean Renewable Energy & Transportation without Greenhouse Gases," WCSF2000 Summit Conference: Energy for the Future, Seoul, Korea, Feb. 10-12, 2000
8. T. R. Galloway, "Clean Renewable Energy & Transportation without Greenhouse Gases," Ninth International Conference: Solutions for the Millennium at United Nations Headquarters, New York, April 26-28, 2000
9. T. R. Galloway, W. L. Millerd, S.J., Reduction of Carbon Emissions From Coal Energy Plants," a white paper presented to the U.S. Office of Science and Technology Policy (White House), November 23, 1998.

10. T. R. Galloway, "Steam-Reforming of Fossil Fuels and Wastes to Produce Energy and Chemicals Without Greenhouse Gases," invited plenary paper for Fourth World Peace Conference, Washington, DC, November 27-30, 1997 and Intersociety Energy Conversion Engineering Conference, Colorado Springs, August 2-6, 1998
11. Forbes, Christian A., "Preliminary Technical Description 250 kW SOFC CHP System," private communication, February 17, 2000.
12. Forbes, Christian A., "Demonstration...The Bridge to Commercialization for Siemens Westinghouse Tubular SOFC," private communication, Alan Casanova, December 29, 1999.
13. Siemens Westinghouse, "Solid Oxide Fuel Cells – The New Generation of Power," private communication, Alan Casanova, December 29, 1999.
14. C. M. Caruana, "Fuel Cells Poised to Provide Power," Chem. Eng. Progr., pp. 11-21, Sept. 1996
15. S. C. Singhal, "Advances in Tubular Solid Oxide Fuel Cell Technology," Proceedings of the 4th International Symposium on Solid Oxide Fuel Cells, Pennington, N.J., Vol 95-1, 195-207 (1995)
16. W. L. Lundberg, "Solid Oxide Fuel Cell/GasTurbine Power Plant Cycles and Performance Estimates," Power-Gen International '96, Orlando, FL, Dec. 4-6, 1996
17. W. L. Lundberg, "100-Kilowatt Solid-Oxide Fuel Cell Tested," Chem. Eng. Progr., pg. 17, December 1997
18. U.S. Dept. of Energy, Office of Fossil Energy, National Energy Technology Laboratory (formerly FETC), "Integrated Gasification Combined Cycle," July 1999. [Recent brochure describing DOE's recommendations for the deployment of the new technology of Integrated Gasification Combined Cycle. Provides a very valuable introduction to this new energy field for the new professional not otherwise acquainted with the historical background and future direction and worldwide strategy.]
19. Private Communication, FuelCell Energy Corp., Danbury, CT, Jan. 1999.
20. Annamalai, K., B. Thien, and J. Sweeten, "Co-Firing of Coal and Feedlot Biomass (FB) in a Laboratory Scale Boiler Burner," 153 pp. 17<sup>th</sup> Annual Int'nat'l Pittsburgh Coal Conference Proceedings, Sept. 11-14, 2000, Pittsburgh, PA.
21. Sweeten, J. M., "Manure and Wastewater Management for Cattle Feedlots," Rev. Environ. Contam. Toxicol, vol 167, 121-153, (2000)
22. T. R. Galloway, Joe Waidl, K. Annamalai, J. Sweeten, T. L. Tomlinson, E. M. Bellet & Dave Weigle, "Energy Resource Recovery Applications Using Gasification and Steam Reforming," paper and presentation at International Conference on Incineration and Thermal Treatment Technologies, New Orleans, LA, May 11-17, 2002.
23. T. R. Galloway, "Why Waste-to-Energy Should be in any Country's Renewable Energy Portfolio," Energy Pulse Weekly: April 10, 2003,  
[http://www.energypulse.net/centers/author.cfm?at\\_id=225](http://www.energypulse.net/centers/author.cfm?at_id=225)
24. T. R. Galloway, & Joe Waidl, "Waste-to-Energy: Why it Should be on any Country's Portfolio," REFocus, The International Renewable Energy Magazine, International Solar Energy Society, pp 30-31, Mar/Apr 2003.

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