GASIFICATION OF DENSIFIED SLUDGE AND WASTEPAPER IN A DOWNDRAFT PACKED-BED GASIFIER

George Tchobanoglous
Nelson W. Sorbo
Department of Civil Engineering
University of California, Davis
Davis, California 95616

Samuel A. Vigil
Civil and Environmental Engineering Department
California State Polytechnic University
San Luis Obispo, California 93407

ABSTRACT

The co-disposal of densified sludge and wastepaper in a co-current flow packed bed gasifier represents a new application of the thermal gasification process. Advantages of this technology include lower costs than other incineration or pyrolysis technologies, simple construction and operation, and the ability to use a variety of fuels including agricultural wastes and other biomass materials in addition to densified sludge and wastepaper.

The disposal of sewage sludge and solid wastes in an economic and environmentally acceptable manner is a problem common to many communities. The co-disposal of sludge and wastepaper in a common facility is a potential solution to both of these problems. The feasibility of the gasification process for the co-disposal of densified sludge and source separated wastepaper is examined in this review.

THE GASIFICATION PROCESS

The gasification of densified sludge and wastewater, a detailed description of a downdraft gasifier, and the important operating parameters that affect the gasification process are reviewed in this section.

Gasification of Densified Sludge and Wastepaper

Gasification involves the partial combustion of a carbonaceous fuel to generate a combustible gas (producer gas) containing carbon monoxide, hydrogen, and some hydrocarbon gases, and a char rich in carbon. A process flow diagram for a complete sludge and wastepaper gasification system is shown in Figure 1. The key elements of the system are: fuel processing, gasification, and gas utilization.

To gasify sludge and wastepaper in a downdraft gasifier, fuel processing is required. A suitable gasifier fuel can be made from source separated wastepaper, sludge, and woodchips by shredding, mixing, and densifying the fuel components. A densification system operated by the Papakube Corporation of San Diego, California was utilized to produce sludge/wastepaper fuels. The Papakube densification system includes an integral shredder, a metering system that allows moistening of the fuel to the optimum moisture content, and a modified agricultural feed cuber. The producer gas can either be used to power an internal combustion engine to generate power or as a fuel for a boiler.

Description of Downdraft Gasifier

Developed originally to reduce the quantities of tar in the producer gas, a downdraft gasifier typically is composed of three subassemblies: 1) a fuel hopper, 2) a firebox, and 3) a charpit. Fuel flow in downdraft gasifiers is by gravity with air and fuel moving co-currently through the reactor. The University of California, Department of Civil Engineering pilot scale batch-fed downdraft gasifier is shown in Figure 2a.

The fuel hopper is constructed as double wall cylinder. The double wall acts as a condensor to remove the water vapor from the fuel prior to gasification. The inner cylinder is in the form of a truncated cone to reduce the tendency for fuel bridging.

The firebox is also a double walled cylinder. The inner cylinder is the actual firebox. Air is supplied by four tubes to the annular space between the walls which serves as an air plenum to distribute air evenly to the six tuyeres (air nozzles) that supply air for partial combustion of the fuel. The choke plate is essentially a large

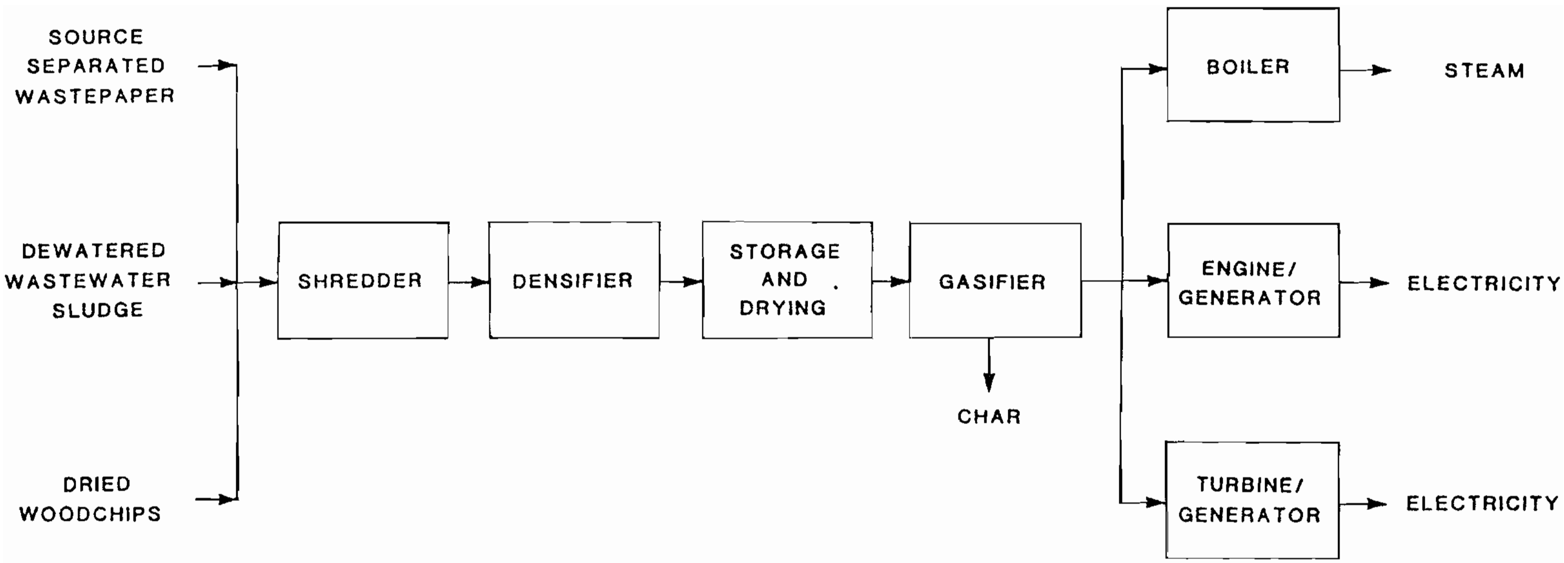

Figure 1. Flow diagram for a complete sludge/wastepaper gasification system.

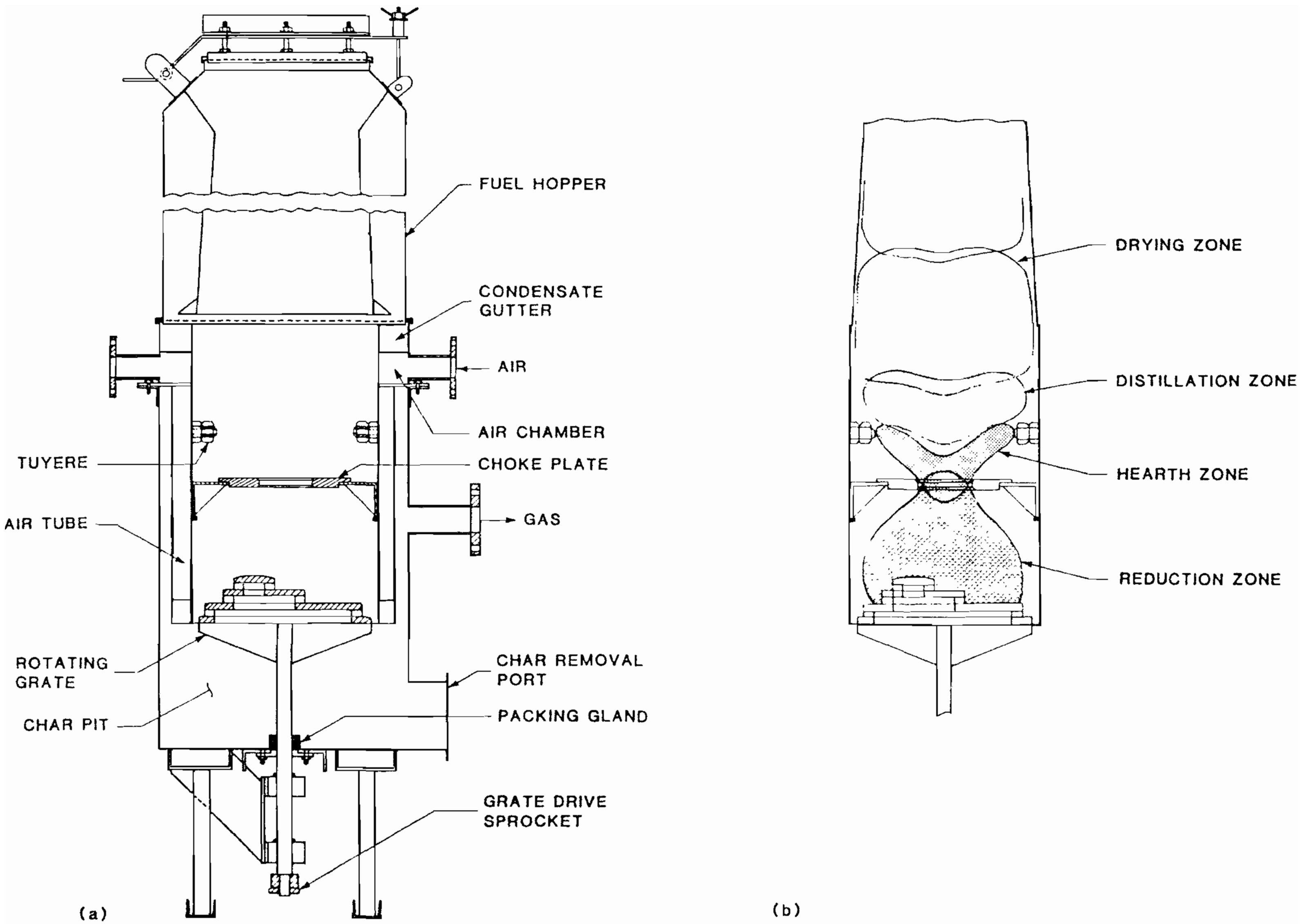

Figure 2. Schematic of UCD Civil Engineering gasifier, (a) internal construction details, (b) reaction zones.

orifice which serves as a constriction in the gasifier firebox, and is used to concentrate both the fuel and gas, creating very high temperatures necessary to thermally crack tars.

A rotating eccentric grate is located in the char pit immediately below the choke plate. The grate supports the fuel bed and allows passage of char and gas into the char pit. Producer gas is drawn off continuously through a pipe manifold on the side of the gasifier. A continuous screw auger is used to convey char from the char pit to a large char storage container. The design of the grate is specific to the fuel and operating characteristics of the gasifier.

Important Gasification Process Operating Parameters

Three operating parameters directly affect the gasification process. They are 1) the fuel ash content, 2) the air input/gasification rate, and 3) the internal gasifier temperatures.

Fuel Ash Content

In addition to lowering the energy content of the fuel, fuel ash, upon reaching its melting point in the gasifier and then cooling, forms slag. Excessive slag formation in a downdraft gasifier can block the flow of fuel and char through the gasifier and thus halt the gasification process. The tendency for slag formation is a function of the reaction zone temperature, the composition of fuel ash, and the percentage of fuel ash (8). To minimize sludge disposal costs, it would be ideal to gasify only sludge in the downdraft gasifier. But because there is sufficient ash in the sludge (between 25 and 40 percent) to cause disruptive slag formations in downdraft gasifiers, slag formation in the gasification of sludge can be inhibited by lowering the reactor temperature and/or mixing additives with the sludge to lower the melting point.

Large reductions in the reactor temperature in a downdraft gasifier to inhibit slag formation are not feasible for two reasons: 1) the energy content and quality (with respect to tar vapor content) of the producer gas varies directly with the reactor temperature; higher reactor temperatures producing a better and cleaner gas; and 2) hot spots will always be present around the air inlet nozzels of downdraft gasifiers, causing slag to form below the nozzels.

A change in the composition of the ash in the sludge can affect the melting point of the ash. Based on an elemental analysis of a sludge/wastepaper fuel, it was found that the phase diagram shown in Figure 3 can be used to estimate the melting point of sludge/wastepaper fuels (17). (The solid triangle shown in Figure 3 is an estimate of the sludge/wastepaper ash melting point, about 1250°C). If lime (CaO) is added to the mixture, it can be seen from Figure 3 that the fuel ash melting point will be raised. (The addition of lime would move the solid triangle in Figure 3 towards the CaO angle, located at the lower left hand corner of Figure 3.)

Vigil proposed the idea of controlling the slagging potential of sludge by adding source separated wastepaper (a low ash fuel) to dewatered wastewater sludge (18). However in municipal sludge/wastepaper gasification systems, if all the wastepaper generated in a community was collected and mixed with all the wastewater sludge generated, the resultant fuel ash content would be about 8.2 percent dry basis (which has caused severe slagging in downdraft gasifiers). Therefore, to derive a useable gasifier fuel from a mixture of wastewater sludge and source separated wastepaper in a community gasification system, wood chips can be added to the mixture. Because the ash content of wood chips is low (0.1-3.0 percent dry basis), a sludge/wastepaper/wood chip fuel mixture can be gasified without disruptive slag formations.

Air Input and Gasification Rate

The air input rate is the most easily controlled operating parameter in the gasification process. In the absence of changes in the fuel composition and gasifier dimensions, the air input rate directly affects the gasification rate and the temperature in the gasifier reaction zone, and indirectly affects the producer gas composition.

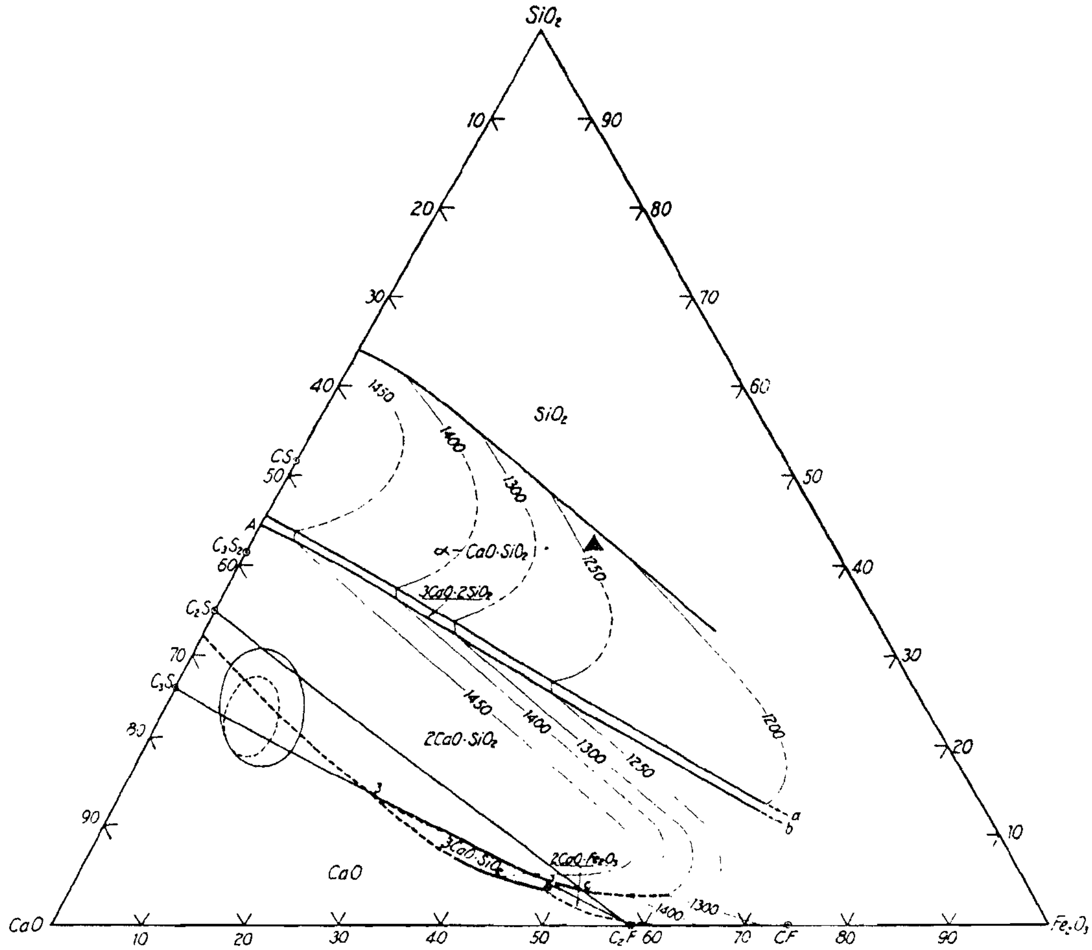

Figure 3. Phase diagram for a $CaO-Fe_2O_3-SiO_2$ system (1).

The specific gasification rate, defined as the gas output rate expressed in mass or volume terms divided by a characteristic gasifier area, is an operational parameter used to compare gasifiers of different size. It is advantageous to operate the gasifier at a high specific gasification rate. The most obvious advantage is that the cost of the gasifier is minimized. Also, a gasifier operated at a high specific gasification rate will maintain a high reactor temperature which is necessary to maintain a producer gas of good quality.

Internal Gasifier Temperatures

The temperature reached in the reaction zone of the gasifier influence greatly all aspects of the gasifier performance. High internal gasifier temperatures affect the process in several ways: 1) tars, higher hydrocarbons and other products of fuel distillation are thermally cracked to non-condensible hydrocarbons in the hearth zone of the gasifier (see Figure 2b), 2) the chemical equilibrium for the formation of CO and H_2 is favored by high temperatures, and 3) the tendency for the formation of slag is affected greatly by the internal gasifier temperature.

DEVELOPMENT STATUS

To investigate the gasification of densified sludge and wastepaper, a pilot scale gasification system was designed and constructed. The operating system consists of three component parts: 1) the batch fed downdraft gasifier, 2) the data acquisition hardware, and 3) the producer gas burner. A complete description of the experimental gasification system may be found in Reference 17.

To demonstrate the gasification process and evaluate air pollution emissions, a broad range of fuels have been tested with the gasifier. Fuels tested include agricultural residue, densified wastepaper, and densified wastepaper and sludge mixtures containing up to 25 percent sludge by weight. The sludge fuels were made from mixtures of lagoon-dried primary and secondary sludge and from recycled newsprint (in full scale systems a mixed paper fraction of solid waste could be used). Mixtures were densified using commercially available equipment.

<u>Summary of Research Findings</u>

A summary of research findings dealing with preparation of densified fuel, maximum fuel ash content, specific gasification rate, gasification process efficiencies, and air pollution emissions is presented below.

Preparation of Densified Fuel

It has been possible to develop a densified fuel from source separated wastepaper and treatment plant sludge using the Papakube densification system. Bulk densities of the sludge/wastepaper fuels ranged from 284 to 595 kg/m^3 (17.7 to 37.1 lb/ft^3). The highest fuel bulk densities are associated with the largest fraction of sludge, which may be taken as an indication that the sludge acts as a binder for the wastepaper during the densification process. The physical integrity of the sludge/wastepaper fuel cubes was dependent on the moisture and sludge contents of the mixture. It was found that sludge/wastepaper cubes of the highest physical integrity were made when the moisture content of the mixture was about 20 percent (wet basis). The physical integrity of the sludge/wastepaper cubes also depended directly on the sludge content of the sludge/wastepaper mixture (over the range of mixtures tested).

Maximum Fuel Ash Content

To date, a fuel with an ash content of 4.85 percent is the highest tested without significant slag formation. Severe slagging occured in the gasifier with a fuel having an ash content of 8.5 percent. Although the addition of lime to the fuel may eliminate some slagging in the high ash fuels, a more conservative fuel ash content of 5 percent (dry basis) can be used as a design number until more experience with full scale sludge/wastepaper gasification systems is obtained.

Specific Gasification Rate

The highest specific gasification rate obtained with sludge/wastepaper fuels was 9500 cubic meters of producer gas ($0^{o}C$, 1 atm) per hour per square meter of choke plate opening area (9500 $m^3/hr \cdot m^2$). This rate is close to the maximum value of 10,000 $m^3/hr \cdot m^2$ reported by Kaupp et al. (8) for small downdraft gasifiers fueled with wood.

Gasification Process Efficiencies

Temperature, pressure, and process rate data were taken during each experimental gasifier run. These data and the results of gas, fuel, and char analyses were used to compute energy balances and process efficiencies. Gasifier process efficiency data from the gasification of a densified sludge/wastepaper fuel at various air input rates are reported in Table 1. The lower heating value of the producer gas generated from the gasification of sludge/wastepaper fuel, reported in Table 1, varied between 5.12 and 5.76 MJ/m^3. Comparable values for sludge digester gas and natural gas are about 22 and 36 MJ/m^3 respectively.

Air Pollution Emissions

Air pollution emission tests were conducted on combusted producer gas over a series of four gasifier runs. Particle emissions were determined using EPA Reference Method 5 and SO_2 emission concentration was determined with a modified EPA Reference Method 6. Concentrations of NO_x and non-condensible hydrocarbons were measured using gas analyzers. The results of these tests can be summarized as follows: 1) Federal particle emissions standards for incinerators were met without the use of flue gas clean-up equipment, 2) concentrations of NO_x varied between 60 and 115 ppm, 3) non-condensible hydrocarbon concentrations, based on hexane, were usually below 1 ppm, 4) concentrations of SO_2 ranged from 0.037 to 0.098 grams per dry cubic meter.

Table 1

GASIFIER PROCESS EFFICIENCIES FOR A SLUDGE/WASTEPAPER FUEL[a]

Air input rate, m^3/min[b,c]	Process efficiencies, percent of net energy input		
	Cold gas	Char	Gas sensible heat
2.02	62	13	14
1.99	64	12	14
2.14	65	10	13

[a] Fuel characteristics: ash content = 4.5 percent dry basis, moisture content = 9.6 percent wet basis, higher heating value (dry fuel) = 16.4 MJ/kg, mixture is 20 percent sludge (@ 40 percent solids) and 80 percent wastepaper (@ moisture content = 10 percent, wet basis) on a wet basis.

[b] Air at 20°C and 1 atmosphere.

[c] Gasifier internal diameter = 0.457m, choke plate orifice diameter = 0.178m.

Full Scale Gasifier Systems

At present there are no full scale gasifier systems operating with sludge/wastepaper fuels. To acquire a full scale gasifier system that can be used in a small community, commercially available gasifier systems originally designed to operate on wood fuels may be purchased and modified or a gasification system specially designed for sludge/wastepaper gasification may be designed and manufactured. The integrated gasification system described in this paper is available for licensing from the University of California Board of Patents.

Commercially Available Gasifier Systems

Kjellstrom (9) reports that there are two companies that manufacture complete wood gasification systems in the 100 to 1000 kW range. They are: Inbert Energitechnik Gmbh (6), and Moteurs Duvant (11). Reed (15) has developed a directory for air biomass gasification systems, both commercial and research. None of the commercially available gasifier systems are designed for sludge gasification.

Design of Sludge/Wastepaper Gasification System for Small Communities

Important criteria for a small community gasification system are that it must be low in capital cost and simple to operate and maintain. A gasifier system that is designed to operate only a fraction of the day can be utilized to sell peak or partial peak power to the local power company. Finally, highly automated gasifier systems are not needed in small communities because of the availability of relatively cheap, unskilled labor.

If a gasifier/engine/generator system is used to generate electricity from sludge/wastepaper fuels it is recommended that: 1) the gasifier/engine/generator system be located at the local wastewater treatment plant, 2) a downdraft gasifier be used because of its ability to generate a producer gas low in tar vapor, and 3) the gasification system be operated in a batch mode rather than in a continuous mode.

TECHNOLOGY EVALUATION

In what follows, gasifier technology is examined with respect to process theory, process capabilities, design considerations, energy analysis, operation and maintenance requirements, and costs.

Process Theory

Gasification of carbonaceous fuels results in the production of a combustible gas known as producer gas, low-BTU gas, or low energy gas. The gas typically contains 10% CO_2, 20% CO, 15% H_2, and 2% CH_4 with the balance of the gas being N_2.

As shown in Figure 2b, four reaction zones are formed in the gasifier. In the hearth zone partial combustion reactions predominate. Heat from these reactions causes pyrolysis reactions to occur in the distillation zone and fuel drying in the drying zone. Endothermic and exothermic water shift reactions, which produce CO and H_2, occur primarily in the reduction zone. The methane found in the producer gas results, primarily, from pyrolysis reactions and thermal cracking, and to a lesser extent exothermic methane reactions. The principal reactions that occur during gasification process are:

$C + O_2 \longrightarrow CO_2 + 3.93.8$ MJ/kg-mol		exothermic	[1]
$C + H_2O \longrightarrow CO + H_2 - 131.4$ MJ/kg-mol		endothermic	[2]
$C + CO_2 \rightleftharpoons 2CO - 172.6$ MJ/kg-mol		endothermic	[3]
$C + 2H_2 \longrightarrow CH_4 + 75.0$ MJ/kg-mol		exothermic	[4]
$CO + H_2O \rightleftharpoons CO_2 + H_2 + 41.2$ MJ/kg-mol		exothermic	[5]

The heat to sustain the process is derived from the exothermic reactions while the combustible components of the producer gas are primarily generated by the endothermic reactions. The probable locations where these reactions occur within the gasifier are identified in Figure 2b.

The above reactions are essentially the same as those that occur in the hearth chamber of the so called "pyrolytic" or "starved air" incinerations (e.g., Consumat or Kelly type modular incinerators). Although the reaction kinetics of the gasification process are quite complex and still the subject of considerable debate, the operation of air blown, downdraft gasifiers of the type used in this research is straightforward. An in-depth discussion of gasification theory and reaction kinetics may be found in References 4, 13, and 14.

Capabilities and Limitations of Downdraft Gasification

The capabilities and limitations of downdraft gasification are technical, economic, and site specific.

Capabilities

The most important attribute of a downdraft gasifier is its ability to produce a relatively clean combustible gas from solid fuels. Thus, producer gas can be used to generate shaft horsepower using an internal combustion engine or gas turbine. Gasifiers coupled directly to a boiler (close-coupled gasifiers) can be used to generate process heat at thermal efficiencies up to 85 percent (15). Gasifiers can also be used to convert existing oil/gas boiler systems to close-coupled gasifier systems, replacing expensive oil and gas fuels with inexpensive soil fuels (15). If pure oxygen (as opposed to air) is used as the oxidant in the gasification process, the product gas (called town gas) can be used in the synthesis of fuels and ammonia.

Downdraft gasifiers are simple and inexpensive to construct and can be scaled down easily. Large amounts of fuel can be gasified by operating several small gasifiers in parallel. In some cases, char, a by-product of downdraft gasification, can be used as a substitute for commercial podered activated carbon, which is used in water treatment (2, 17).

Limitations

The most fundamental limitations of downdraft gasification deal with the fuel. The fuel requirements are: 1) fuel moisture content less than 20 percent, 2) fuel ash content less than 5 percent, 3) uniform fuel grain size, and 4) a sufficient density to permit flow by gravity.

Although downdraft gasifiers are originally designed to produce tar free gas, in practice some tars are always present in the producer gas. Because tars can foul boilers and coat the internal mechanisms of internal combustion engines, tars must be removed from the producer gas. The removal of tars from producer gas is one of the most common and difficult problems encountered in downdraft gasification. Thus, producer gas clean-up equipment is required for most gasifier applications. Because of its low heating value, it is not economical to store or transport producer gas. Therefore, producer gas should be used onsite.

Design Considerations

Three critical areas of downdraft gasifier design involve 1) the internal gasifier dimensions (firebox diameter, length of reduction zone, choke plate orifice diameter), 2) the design of the grate, and 3) the method of air injection. Though designs from wood gasifiers can be used as a starting point, it must be emphasized that all aspects of the gasification system must be designed around the fuel to be utilized and the operating condition of the gasifier.

Energy Analysis

Sludge/wastepaper fuels can be converted to electricity at a gross energy efficiency of about 21 percent. Fuel processing and internal gasifier energy requirements are approximately 3 percent of the energy input, resulting in a net efficiency of 18 percent.

Operation and Maintenance

Because there are no full scale sludge/wastepaper gasification plants in operation, it is difficult to give precise estimates of the operation and maintenance costs (O&M). For wood gasification plants of 50 kW or greater, operation costs have been estimated to be 5.3 hours of labor per 1000 hours of full power operation per kilowatt of output (9).

Capital Costs

Capital cost for gasification systems are usually based on electric power output. Installed costs for wood gasification power plants vary from $750/kW for a batch fed unit to $1500/kW for a fully automated unit. These costs do not include fuel processing. Estimates of fuel processing costs for a sludge/wastepaper gasification system vary between 48 and 80 dollars per wet tonne of fuel. Fuel processing costs include wastepaper processing, purchase of wood chips, sludge dewatering, and mixing/shredding/densification of the fuel mixture.

COMPARISON WITH EQUIVALENT TECHNOLOGIES

There is no equivalent technology to the gasification of sludge and wastepaper as described in this paper. Although sludge and refuse derived fuel (RDF) were experimentally gasified in the PUROX pyrolysis system (3,10) and in a modified multiple hearth furnace operating in the "starved air" mode, neither process has been commercialized. Both processes were designed for larger communities with populations greater than 100,000.

Cost

To estimate the total cost of sludge disposal associated with a sludge/wastepaper gasification system, a detailed economic analysis was performed in Reference 16. The sensitivity of sludge/wastepaper gasification system costs to the cost of wood chips and to the resale value of power is shown in Figure 4. These costs were calculated for a community size of 50,000. Further, it was assumed that 40 percent of the total wastepaper collected in the community is mixed with both the sludge and wood chips to form the gasifier fuel. The costs were indexed to an Engineering News Record Construction Cost value of 3610.

Based on the results presented in Figure 4, it is clear that the resale value of electricity and the cost of woodchips influence greatly the economic viability of sludge/wastepaper gasification systems. However, because both the resale value of

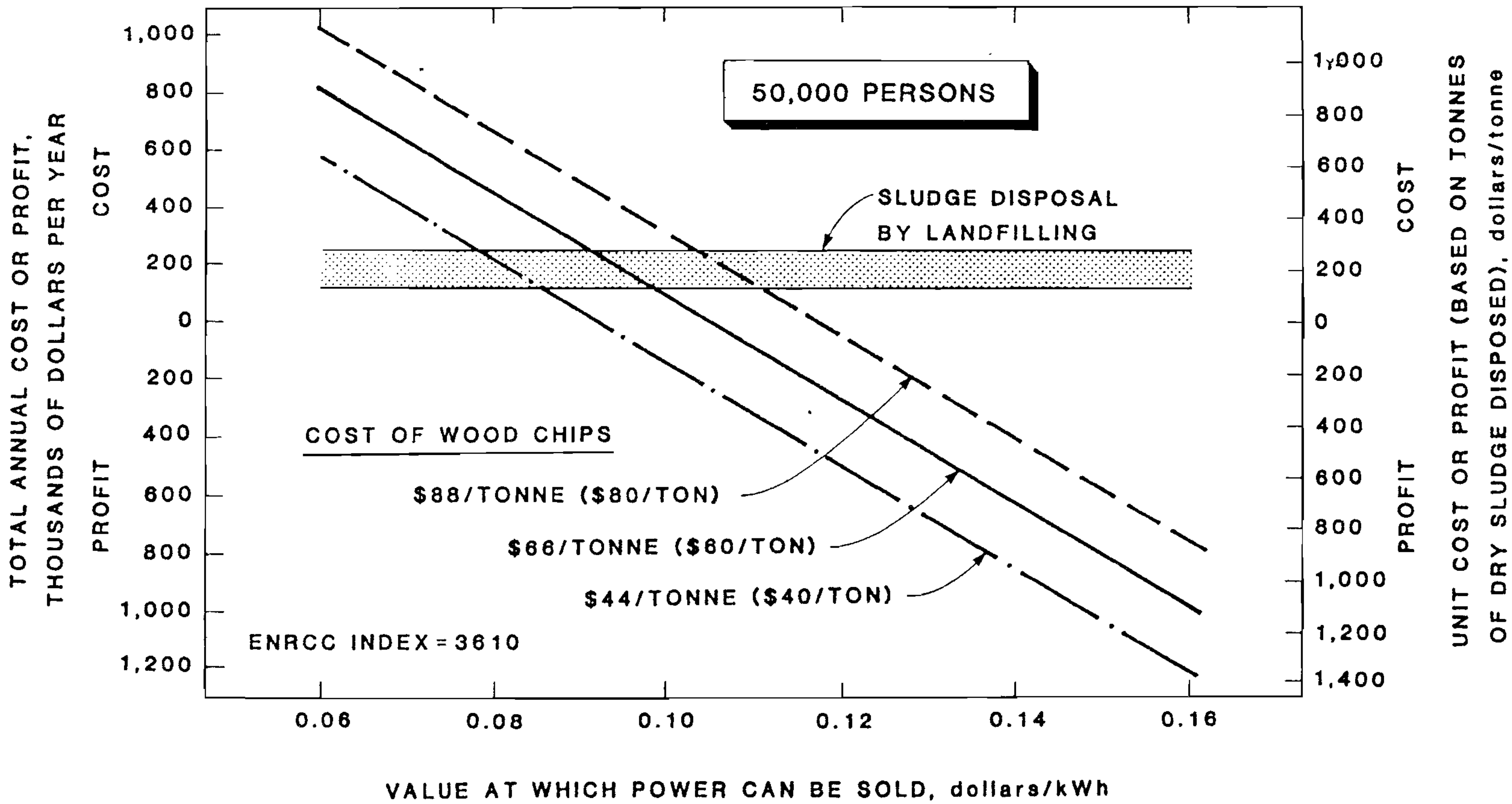

Figure 4. Estimated total annual cost or profit for the disposal of sludge and wastepaper in a gasification system for a community of 50,000 persons (adapted from Reference 16).

electricity and the cost of woodchips influence greatly the economic viability of sludge/wastepaper gasification systems. However, because both the resale value of electricity and the cost of woodchips are highly site specific, it is difficult and inaccurate to conclude anything about the economic feasibility of gasification over large areas. Rather, each community must be considered individually. A range of resale values of electricity would probably be between 0.03 and 0.10 $/kWh in most areas of the country. Therefore, according to the results presented in Figure 4, the economic feasibility of sludge/wastepaper gasification ranges from unprofitable to marginally profitable.

Performance and Reliability

Until more development work has been done and a prototype system built, the reliability of a full size system cannot be estimated. However the laboratory scale unit described in this paper has proven itself to be reliable in over about 150+ hours of operation. Because over 100,000 automotive wood fueled gasifiers were operated during World War II it can be assumed that gasifiers are reliable and easy to repair. The operation of downdraft gasifiers is reliable when operated by experienced personnel and with a relatively uniform fuel composition. The densification and fuel processing equipment is based on commercially available agricultural equipment which has proven to be extremely reliable. Thus it can be assumed that a full scale sludge gasifier system would tend to be as reliable as the basic components.

Environmental Benefit

Sludge/wastepaper gasification has some environmental advantage over conventional sludge combustion technologies. Based on estimated uncontrolled emissions from multiple hearth incinerators burning sludge and refuse, reported in Reference 12, and sludge/wastepaper gasification results reported in Reference 17, the following conclusions can be drawn. First, uncontrolled particle and hydrocarbon emissions from the sludge/wastepaper gasification system are significantly lower than those reported for sludge/refuse multiple hearth incineration. Second, uncontrolled

SO_2 emissions from the gasification of sludge/wastepaper are approximately equal to estimated values for sludge/refuse multiple hearth incineration. Third, uncontrolled NO_x emissions from the sludge/wastepaper gasification system are 2 to 3 times higher than the estimated values for sludge/refuse multiple hearth incineration. It must be noted that during the operation of the sludge/wastepaper gasifier, no effort was made to modify furnace conditions to control emissions. Therefore, full scale sludge/wastepaper gasification systems should have comparable or lower emissions than conventional incinerators.

Toxic Management

The potential exists for the generation of small amounts of tar from the gas clean up train. This material could be reinjected into the gasifier for energy recovery and treatment. The fate of heavy metals is being determined in ongoing research.

Joint Treatment Potential

The gasification system is an integrated co-disposal system for small communities. It allows for the disposal of sludge, wastepaper, and agricultural some residues in a common system.

NATIONAL IMPACT ASSESSMENT

Because the sludge/wastepaper gasification process has not yet been commericalized its national impact can only be speculated. As most wastewater treatment plants in the United States are small, the impact of the availability of a small scale thermal process for sludge management could be significant. The process would allow energy recovery from currently wasted resources, wastepaper and sludge.

As in any new technology, there is risk associated with its adaption. However based on the experimental work to date it has been shown that if the fuel limitations with respect to moisture, ash content, and grain size are dealt with properly, gasifiers can be used with little or no risk.

RECOMMENDATIONS

The technical feasibility of operating a packed-bed gasifier with densified sludge/wastepaper mixtures has been demonstrated. Recommendations for further research and development and process modifications are as follows.

Future Research and Development

Before the sludge/wastepaper gasification process can be considered operational, however, several key issues must be addressed in future work.

1. The optimum conditions for gasifier operation in terms of fuel consumption, air flow, gas quality, and efficiency need to be defined. These parameters are needed to develop loading factors and specifications for the design of full scale systems.
2. Conditions causing slagging should be determined. Slag control measures such as steam or water injection, or continuous grate rotation should be investigated.
3. The fate of heavy metals during the gasification process must be determined.
4. Mass emission rates and particle size distributions for particulates in the producer gas should be measured to provide data for the design of gas cleaning equipment.
5. Emission data from engines, burners, and boilers fueled with producer gas should be measured. Emissions should also be analyzed for potentially toxic compounds.

Process Modifications

Important modifications that may further improve the economic and technical feasibility of the gasification process are:

1. Development of a suction gasifier that can be operated with an open fuel hopper.
2. Development of slagging type gasifier for use with less optimum fuels.

3. Development of a simple plug flow gasifier that would eliminate the need for a choke plate.

4. Development of gasifier that would operate with a fuel that requires less processing vis-a-vis the fuel cubes used in the UC Davis gasifier.

ACKNOWLEDGEMENTS

The assistance of Professor J.R. Goss, of the Department of Agricultural Engineering, University of California, Davis, is acknowledged gratefully. The research work discussed in this paper was supported by grants from the University of California Appropriate Technology Program and the U.S. Environmental Protection Agency.

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