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HYDROGEN PRODUCTION BY SUPERCRITICAL WATER GASIFICATION OF BIOMASS

PHASE I - TECHNICAL AND BUSINESS FEASIBILITY STUDY TECHNICAL PROGRESS REPORT

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ABSTRACT

HYDROGEN PRODUCTION BY SUPERCRITICAL WATER GASIFICATION OF BIOMASS

General Atomics (GA), in cooperation with the University of Hawaii at Manoa, performed a Phase I study to develop technical and business plans for a cost-effective, environmentally attractive method for production of hydrogen from biomass, specifically from sewage sludge (i.e., biosolids). The nine-month Phase I feasibility study was directed toward the application of supercritical water gasification (SCWG) for the economical production and end use of hydrogen from renewable energy sources such as sewage sludge, pulp waste, agricultural wastes, and ultimately the combustible portion of municipal solid waste. Unique in comparison to other gasifier systems, the properties of supercritical water (SCW) are ideal for processing biowastes with high moisture content or contain toxic or hazardous contaminants. Thus, a niche field of application is proposed favoring SCWG.

During Phase I, an end-to-end SCWG system was evaluated. A range of process options was initially considered for each of the key subsystems. This was followed by tests of sewage sludge feed preparation, pumping and gasification in GA's SCW pilot plant facility. Based on the initial process review and successful pilot-scale testing, engineering evaluations were performed that defined a baseline system for the production, storage and end use of hydrogen. The results compare favorably with alternative biomass gasifiers currently being developed. The results were then discussed with regional wastewater treatment facility operators to gain their perspective on the proposed commercial SCWG systems and to help define the potential market. Finally, the technical and business plans were developed based on perceived market needs and the projected capital and operating costs of SCWG units. The result is a three-year plan for further development, culminating in a follow-on demonstration test of a 5 MT/day system at a local wastewater treatment plant.

The baseline system defined in Phase I includes steps for feed preparation (sewage sludge blending, maceration, dewatering, liquefying, and ash removal), liquefied feed pumping and preheating, sludge gasification, heat recovery, pressure letdown, hydrogen separation via membrane and pressure swing adsorption units, hydrogen storage in medium pressure tanks, and hydrogen end use as "across-the-fence" sales or for power production in fuel cells and/or advanced gas turbines.

Economic projections show that SCWG processing of sewage sludge provides municipal wastewater facility operators with a cost-effective means for disposal of primary and secondary sewage sludges, compared with current disposal costs, and for generating hydrogen and steam that can serve as potential sources of revenue to offset upstream treatment costs. The analyses also show that the SCWG capital cost for a 27 MT/ton day system - a size suitable to treat the sewage sludge of over 200,000 residents - is comparable with those of alternate biomass gasification methods, but that operating costs are much more favorable (i.e., negative). Furthermore, the favorable economics are fairly insensitive to the composition and hydrogen yield of the gasified product.

Compared to other biomass gasifiers, SCWG is ideal for feedstocks with high moisture content (such as sewage sludge) as well as wastes with toxic or hazardous contaminants (such as heavy metals or halogenated compounds). This high-pressure aqueous medium enables concentration and treatment of challenging feedstocks while providing in-situ scrubbing of hazardous materials.

Nearly all the key process operations have been demonstrated. However, technical data gaps are identified that must be resolved to verify assumptions made in the Phase I study. Second-generation advancements are also noted that could further enhance SCWG system performance and economics.

The SCWG Development Plan addresses the follow-on work included in the proposed Phase II ("Technology Development"), Phase III ("Technology Validation") and Phase IV (Demonstration of Scale-Up"), culminating in follow-on, near-commercial pilot-scale demonstration of sewage sludge gasification at a regional wastewater treatment facility. The plan also addresses the initial design and marketing efforts for commercial-scale systems.

During the technology development phase, key technical issues identified in Phase I will be addressed by way of additional testing in the GA SCW facility. During the technology validation effort, elements of a 5 MT/day pilot facility will be designed, procured and tested as stand-alone subsystems. During demonstration of scale-up, the individual subsystems will be integrated into a complete skid-mounted system and tested to demonstrate gasification of sewage sludge and hydrogen production.

Following completion of the GA/Department of Energy (DOE) joint development program, the 5 MT/day pilot plant will be moved to a local wastewater treatment facility and operated for an extended period to demonstrate reliable, long-term operation. Based on the lessons learned

during the GA/DOE program and near-commercial demonstration, GA will initiate commercialization efforts, including the design and marketing of the 27 MT/day commercial SCWG system.

The overall results from the technical and business plans reasonably establish that with continued development, SCWG treatment of sewage sludge can be a viable and competitive commercial process for the production of hydrogen, particularly for the niche feedstocks evaluated. Furthermore, the plans show that, under continuing DOE support, development and commercialization can be achieved in as little as five years.

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ABBREVIATIONS AND ACRONYMS

APS	Advanced Process System
ASME	American Society of Mechanical Engineers
BCL	Battelle Columbus Laboratory
biosolids	sewage sludge
DARPA	Defense Advanced Projects Research Agency
DoD	Department of Defense
DOE	Department of Energy
GA	General Atomics
GAC	granular activated carbon
HC	hydrocarbon
M&EB	mass and energy balance
MT	metric ton
NASA	National Aeronautics and Space Administration
NO _x	nitrogen oxides
PFD	process flow diagram
ppm	parts per million (1 part in 10 ⁶)
PSA	pressure swing adsorption
psi	pounds per square inch
SCW	supercritical water
SCWG	supercritical water gasification
SCWO	supercritical water oxidation
SO _x	sulfur oxides
WHSV	Weight hourly space velocity

I. PROJECT SUMMARY

General Atomics (GA) has performed a Phase I study for development of Supercritical Water Gasification (SCWG) as a cost-effective, environmentally attractive method for the production of hydrogen from biomass fuels, in particular sewage sludge. This technical progress report summarizes the results of the nine-month Phase I feasibility study and presents technical and business plans for continued development of SCWG technology to near-commercial status. The technical plan describes the key issues for the development of SCWG and the manner in which they will be addressed as part of the design and testing of a 5 MT/day pilot-scale system. The business plan defines the steps required to bring SCWG into the commercial arena. The overall report is presented in the format called for in the Department of Energy (DOE) Solicitation for Financial Assistance Applications (Solicitation No. DE-PS36-96GO10160). The following sections present a summary of the Phase I testing and evaluation; the proposed technical approach and accompanying business plan for Phase II, Technology Development, Phase III, Technology Validation, and Phase IV, Demonstration of Scale-Up; and the budget requirements for Phases II through IV.

I.A TECHNICAL APPROACH

GA performed a Phase I feasibility study over a period of nine months which definitized a three-year development and demonstration plan for Phase II through Phase IV. In Phase I, we evaluated an end-to-end integrated system based on SCWG. We considered a range of options for each of the key subsystems, performed engineering evaluations and pilot-scale tests for key SCWG process steps, and formulated technical development and business plans. Our approach focused on demonstrating SCWG of sewage sludge, followed by direct use of the high-value process gas.

The results of the Phase I testing were successful in verifying, at pilot-scale, the general range of results of Prof. Antal at the University of Hawaii at Manoa (gasification yield, hydrogen production), as well as concentration and pumping of sewage sludge at solids concentrations up to 10 wt% (See Appendix B). The results of the Phase I feasibility study were successful in defining commercially available systems and components that, together with SCWG technology based on similar SCWO systems, project yields of hydrogen and steam that equal or surpass the output of other gasifiers and show that SCWG is a technically and economically viable method for hydrogen production from sewage sludge.

The proposed technical approach for Phases II through IV builds on the successful testing and development activities performed during Phase I of the GA/DOE program. During Phase II, key technical issues identified during the initial review of the baseline process design and pilot-scale testing will be addressed. These include sewage sludge feed preparation and pumping tests (Task 100), laboratory-scale tests with granular activated carbon (GAC) and alternate catalysts, and extended pilot-scale tests incorporating a liquefied sewage sludge feed system and the optimum SCWG catalyst (Task 200). Chemical equilibrium analyses will also be performed and compared to laboratory- and pilot-scale test results (Task 300). These will then be followed by preparation of the process flow diagram (PFD), mass and energy balances (M&EBs), and interface requirements for the SCWG subsystems to be tested during Phase III (Task 400). These activities, supported by project management (Task 500), are scheduled to require 12 months.

During Phase III, systems analyses will be performed to address key safety; reliability, availability, and maintainability (RAM); and permitting issues (Task 100). A system design effort will also commence at the same time that will result in design packages for SCWG subsystems and components, as well as definition of pilot plant facility upgrades and support needs for subsystem testing (Task 200). This will be followed by equipment procurement, assembly and testing of SCWG subsystems at GA, including acquisition of support subsystems [e.g., membrane separation and pressure swing adsorption (PSA) units] (Task 300). This phase, including project management (Task 400), is anticipated to require 12 months.

During Phase IV, the subsystems will be assembled into an integrated 5 MT/day SCWG gasification system and the pilot plant will be prepared for extended testing (Task 100). The system will then undergo check out with both simulant feed and actual sewage sludge (Task 200). Extended tests of the integrated system will then be performed with sewage sludge and the final report written and issued (Task 300). Together with project management (Task 400), this phase should have a 12-month duration.

Although not part of the proposed GA/DOE SCWG development program, the pilot plant will be moved to a regional wastewater treatment facility and operated for a year to gain first-hand experience to assist with development of a commercial-size 27 MT/day SCWG system. This system will then be marketed to the wastewater treatment industry for sewage sludge treatment and hydrogen production.

I.B BUSINESS PLAN FOR PHASES II - IV

The business plan for Phases II through IV is directly coupled to the technology development effort. GA plans to continue its interaction with the Encina Wastewater Authority located in Carlsbad, CA, approximately 10 miles north of GA. Encina was a pivotal contributor to the Phase I effort, providing useful insight into the wastewater treatment industry, sewage sludge processing and disposal practices, and all sewage sludge used during testing. During each of the proposed phases, GA will provide Encina with updates on progress to date and address their feedback on ways to make the process and system increasingly acceptable to the wastewater industry. As the technology is developed during Phases II, III and IV, GA plans to disseminate the program findings to industry forums, including meetings, conferences and seminars. At the end of Phase IV, GA plans to form a strategic alliance with a wastewater treatment facility to demonstrate long-term on-site operation of the 5 MT/day pilot plant.

Throughout the GA/DOE program, we will continue to refine our estimates of capital and operating costs, potential markets for the technology, and likely returns to investors. We will stay abreast of developments in alternate means of generating and purifying hydrogen and in hydrogen end uses. Thus the business plan activities during Phases II through IV will be focused on providing the springboard for full commercial development of SCWG in the years following the successful completion of the program.

I.C BUDGET REQUIREMENTS FOR PHASES II - IV

Table I-1 presents the budgetary requirements for Phases II through IV of the program for both GA and DOE. They are based on the projected budgets for each phase presented in the business plan (see Sec. III.A.3) and the allowable levels of DOE funding.

Table I-1. DOE Funding Requirements and GA Cost Share

Phase	Budget (\$)	DOE Share (\$)	GA Share (\$)
Phase II, Technology Development	1,287,750	1,030,200	257,550
Phase III, Technology Validation	3,364,235	2,691,388	672,847
Phase IV, Demonstration of Scale-Up	993,697	496,849	496,848
Total for all phases	5,645,682	4,218,437	1,427,245

II. TECHNICAL APPROACH

SCWG is a process for converting organic materials, in particular, biomass, into useful product gases in water at temperatures and pressures above the critical point of water, 374°C and 22.1 MPa (3200 psi). A notable feature of supercritical water (SCW) is the marked change in its thermophysical and chemical properties near the critical point. In the supercritical region, properties of water such as density, dielectric constant, viscosity, electrical conductance, specific heat, thermal conductivity, and solvating power are quite different from liquid water or steam. In the supercritical region, water behaves like a nonpolar organic solvent. Organic compounds that are only sparingly soluble in normal liquid water become completely miscible with SCW. Many gases, such as oxygen and nitrogen, are also completely miscible with SCW. Conversely, while SCW is an excellent solvent for organics and gases, it is a poor solvent for inorganic salts. Salts precipitate at SCW conditions, and insoluble metal oxides and other contaminants such as heteroatoms remain in the aqueous phase. Thus, SCW acts as an in-situ scrubber by selectively removing contaminants from the gas phase. It is the combination of these properties that promote the efficient gasification of biomass. Gasification is accomplished under homogeneous, single-phase conditions that provide excellent mixing and high mass and heat transfer rates. Reaction kinetics are rapid, requiring relatively short residence times and a small reaction vessel to achieve high gasification rates.

The impetus for GA's interest in SCWG is its experience in closely related technology, supercritical water oxidation (SCWO), which has been under development at GA for the past 15 years and is currently highly developed for the destruction of toxic and hazardous wastes. A wide variety of Government applications are currently being demonstrated for such diverse feedstocks as chemical warfare agents, solid propellants, mixed wastes, shipboard hazardous wastes, and human wastes generated during space flight. GA is the leading developer of SCWO technology, performing many of the key development programs mentioned above. GA has pioneered many advances in SCWO technology, and holds over ten key patents in the field. GA operates three SCWO pilot plants with capacities in the range of 2.0 to 6.0 l/min total flow, and is currently designing and fabricating several special-purpose SCWO systems with capacities up to approximately 15 l/min. Many of the advanced methods developed for SCWO can be applied directly to SCWG technology and to scale up the process to pilot-then-commercial scale.

Gasification of biomass in SCW has been studied extensively since the mid-1970s as a cost-effective, environmentally attractive means of producing hydrogen and other energetic

gaseous fuels. Laboratory-scale SCWG work performed by Antal and coworkers at the University of Hawaii at Manoa has recently demonstrated very high yields of hydrogen from a variety of biomass feeds, including sewage sludge. These findings and GA's experience in SCWO were the starting points for Phase 1 of the program to develop integrated SCWG systems for hydrogen production and use. During this phase, a technology survey was performed to provide the latest information on key aspects of GA's baseline approach and options (Task 100). This was followed by a series of tests performed in GA's SCW pilot plant with sewage sludge obtained from the Encina Wastewater Authority located in Carlsbad, CA (Task 200). In parallel with these activities, an integrated system component evaluation was performed to define the optimum system for SCWG hydrogen production (Task 300). This was followed by energy, environmental and economic evaluations of the SCWG system (Task 400), along with safety, reliability and regulatory evaluations (Task 500).

The findings of Tasks 100 through 500 are generally summarized herein as part of the technical and business plans. The mass and energy balances (M&EBs) for the finalized process flow diagram (PFD) (which show high yields of hydrogen production and steam) are presented in Appendix A. A test report for Task 200 is included in its entirety as Appendix B. The other tasks are documented in progress reports.

Based on information in Tasks 100 through 500, the technical development plan for the selected approach was prepared (Task 600). In addition to technical evaluation of the integrated SCWG system, a market analysis was performed and a business plan developed for follow-on phases and commercial activities (Task 700).

The following sections describe the specific elements of our approach. Integrated system performance parameters are first defined based on (1) sewage sludge processing needs at regional and national wastewater treatment facilities, and (2) scaleup of the GA SCW pilot plant (Sec. II.A). Having defined the optimum process configuration and throughput for both commercial acceptance and low-cost hydrogen production, the developmental status (Sec. II.B.1) and technology development requirements for individual components and subsystems (Sec. II.B.2) are described. This is followed by a description of the integrated SCWG system (Sec. II.C), including proposed solutions to critical systems integration issues and barriers to SCWG implementation and potential solutions (Sec. II.D).

II.A INTEGRATED SYSTEM PERFORMANCE PARAMETERS

During Phase I of the project, the preliminary SCWG process was evaluated by means of literature reviews, contacts with major system component vendors, SCWG pilot plant tests

performed at GA, and system modeling studies. This led to the revised block flow diagram for the integrated SCWG process shown in Fig. II-1. The block flow diagram lists the key steps of the process and the major sub-elements of each step.

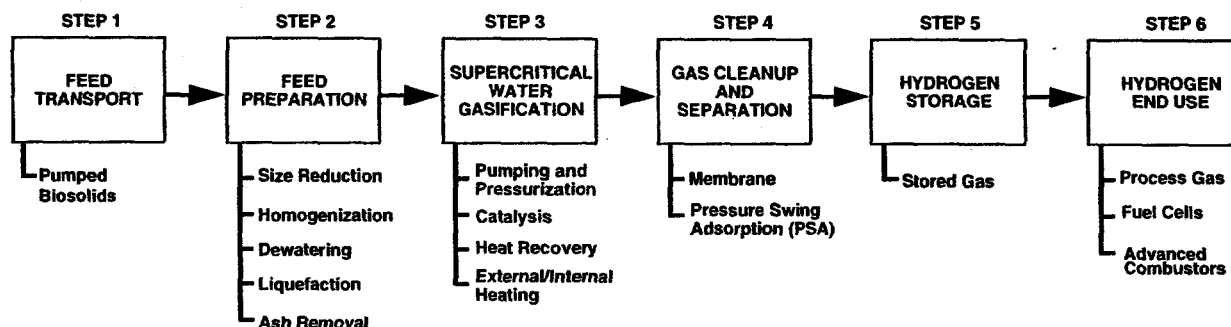


Fig. II-1. Block flow diagram for integrated SCWG hydrogen system

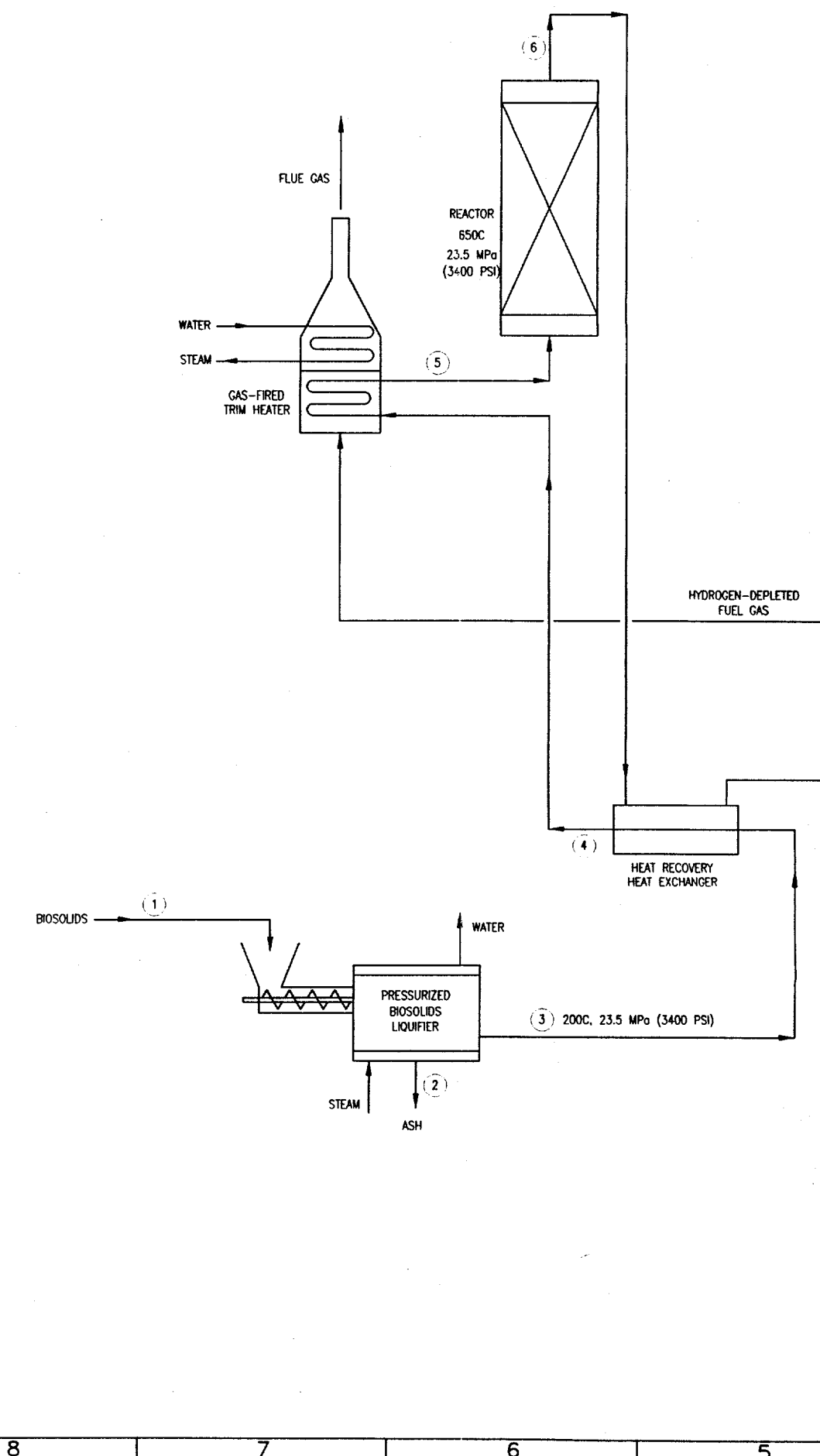
After initially defining the primary elements of the integrated system, a PFD and accompanying M&EBs were prepared for the system, as described below. These formed the initial basis for evaluating the technical and business merit of hydrogen production via SCWG of sewage sludge. The block diagram and PFD were revised based on results of the M&EB and cost analyses. Thus the cost drivers were used to select the optimum technical approach.

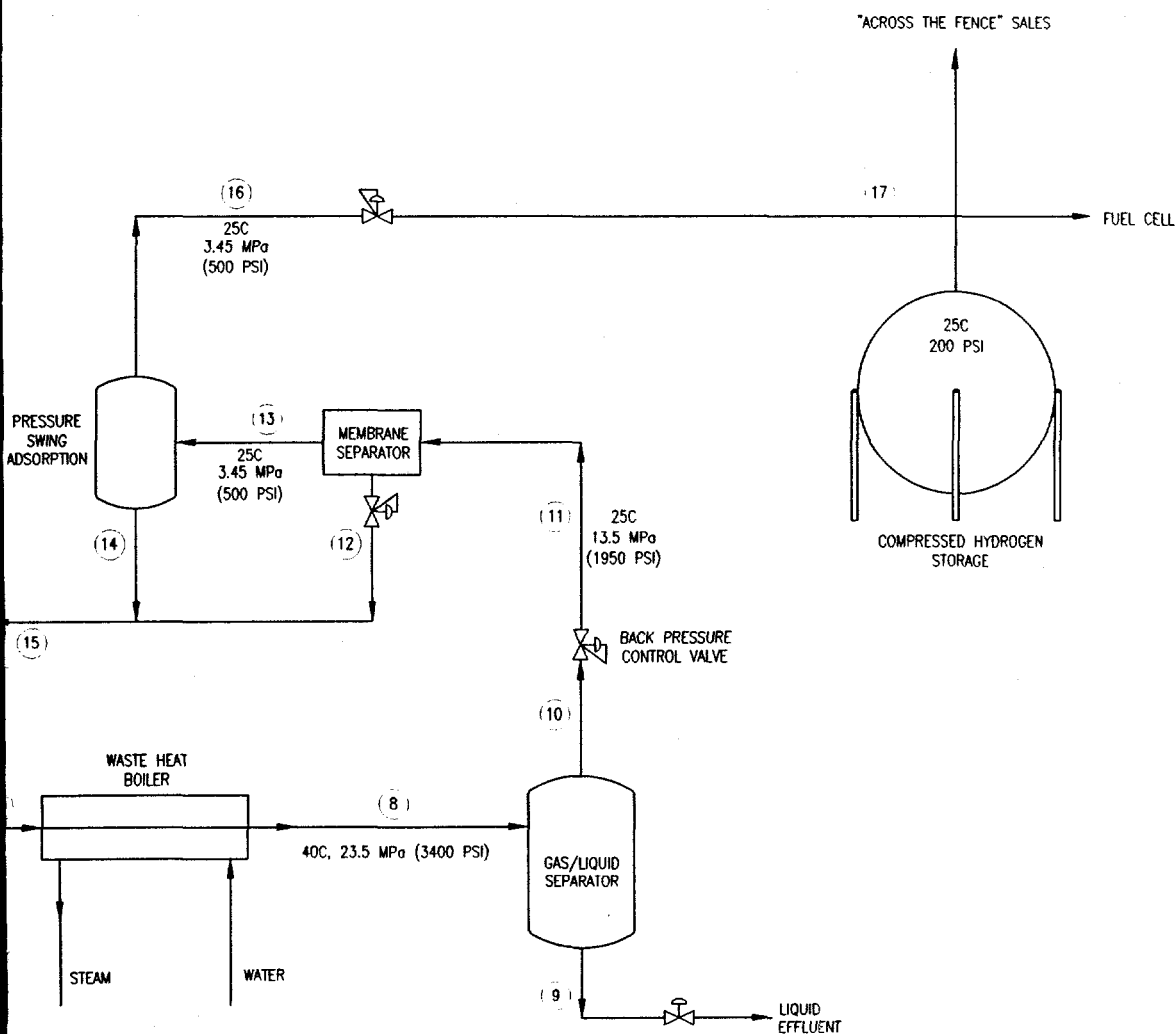
II.A.1 Process Flow Diagram

The proposed PFD for the treatment of municipal sewage sludge (referred to as biosolids in the commercial wastewater treatment industry) is shown in Fig. II-2. Mixed primary and secondary sludges from a municipal wastewater treatment plant are macerated, homogenized and dewatered to a combustible solids content of up to 40 wt% (Stream 1). The dewatered solid is then augered into a pressurized sewage sludge liquefier heated with process steam. During liquefaction, inorganic material, referred to for convenience as ash, settles to the bottom of the liquefier and is withdrawn from the process (Stream 2). The liquefied feed is then pumped to the system operating pressure of approximately 23.4 MPa (3400 psi) (Stream 3) and preheated in two stages - first, in a heat recovery heat exchanger (Stream 4) and second, in a gas-fired trim heater (Stream 5). The hot flue gas from the gas-fired heater is used to produce steam for export or other in-plant uses. Having been preheated to the gasification temperature of 650°C, the process stream enters the gasification reactor containing a GAC bed. Based on

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observations during pilot scale testing, the gasification reactions are assumed to be thermally neutral, resulting in an stream exit temperature of 650°C (Stream 6). Next, the process stream gives up part of its heat to preheat the feed in the heat recovery heat exchanger (Stream 7), and is then cooled to near-ambient temperature in a waste heat boiler. A portion of the steam produced by the waste heat boiler is used to heat the pressurized biosolids liquefier, with the remainder of the steam available for export or other in-plant uses. Subsequent to cooling, but still at essentially full pressure, the process stream enters a gas-liquid separator (Stream 8). The liquid phase, comprising water, a significant fraction of the CO₂, and a small fraction of dissolved and entrained ash, exits from the bottom of the separator (Stream 9) and is depressurized. The depressurized liquid effluent is then returned to the wastewater treatment plant for final discharge.

The high pressure gas stream exiting the separator (Stream 10) is fed to a membrane separator after being depressurized to 13.4 MPa (1950 psi) (Stream 11).¹ The membrane separator recovers about 90% of the H₂, passes about 40% of the CO₂ and CO, and reduces the CH₄ content by an order of magnitude (Pope, 1997). The pressure of the hydrogen-enriched permeate stream drops about 10.0 MPa (1450 psi) across the membrane to yield an outlet pressure of 3.45 MPa (500 psi) (Stream 13). This represents the maximum feed pressure to a conventional PSA unit (Rarig, 1997)¹. The membrane system also raises the hydrogen content of the stream above 70%, the minimum required for feed to the PSA unit. PSA removes all contaminants down to parts per million (ppm) levels while recovering about 80% of the hydrogen at essentially feed pressure. The off gas from the PSA unit (Stream 14) is combined with the depressurized off gas from the membrane separator (Stream 12), and the hydrogen-depleted gas mixture is used to fuel the gas-fired trim heater (Stream 15). Hydrogen from the PSA unit (Stream 16) is subsequently depressurized to about 1.38 MPa (200 psi) for storage (Stream 17). Such relatively low pressure storage is practiced using spherical vessels with a volume of about 15,000 m³ (Haussinger, et al., 1985). From the storage vessel, the hydrogen may be supplied for various end uses, e.g., "across-the-fence" sales or power generation by fuel cells or by advanced gas turbines.

¹ Note that much of the pressure at which the hydrogen is produced is wasted in order to utilize commercially available membrane and PSA units. Second generation improvements may be possible to utilize higher system pressures and further improve process economics.

II.A.2 Mass and Energy Balances

M&EB calculations were carried out for the flow scheme of Fig. II-2 for 20 wt% and 40 wt% combustible sewage sludge contents with 1% ash. A plant size of 27 metric tonnes/day (MT/day, equal to 30 English tons/day) of combustible solids was evaluated since it is compatible with the throughput of a fairly typical municipal wastewater treatment works. This size also allowed direct comparison with a previous study of the Battelle Columbus Laboratory (BCL) biomass gasifier configured for the production of hydrogen (Mann, 1995) (see Sec. III.B.2). Results of the M&EBs are presented in Tables II-1 and II-2 and in Appendix A. The calculations incorporate typical hydrogen yields for sewage sludge of ~ 43% (Antal 1997) and the best hydrogen yield reported to date, a mole fraction of ~53% hydrogen, achieved for an approximately 50/50 mix of poplar sawdust and corn starch (Antal, 1997b). It is assumed that the higher yields can be attained on de-ashed sewage sludge since it is less oxygenated than woody biomass and has a higher percentage of carbon and hydrogen. While this assumption remains to be verified, the overall process economics for SCWG [which are evaluated for both yields (43% and 53% hydrogen) and presented in the M&EBs in Appendix A and in the business plan (Sec. III)], are relatively insensitive to the variations in hydrogen yield from 43% to 53%, which is a major conclusion of our feasibility study. As explained later, process economics drive the design to high concentrations (40 wt%) of sewage sludge.

Other assumptions and data used in the M&EB calculations include the following:

- Filter press is used to concentrate incoming sewage sludge to 40%
- Reaction conditions of 650°C and 23.5 MPa (3400 psi).
- Thermally neutral reactions (see discussion in Section IIB.2). No heat loss in gasifier, heat recovery heat exchanger, waste heat boiler, or associated piping.
- Lower heating value of fuel gas in trim heater.
- Biosolids liquefier reduces ash content of sewage sludge from 25 wt% to 1 wt%.
- Sewage sludge ash purged from the liquefier at 50 wt% in water.

Table II-1. SCWG M&EB for 20 wt% Sewage Sludge Feed (27 MT/day)

Stream No.	1	2	3	4	5	6	7	8
Stream Name	Sewage sludge Feed	Liquefier Ash Purge	Liquefier Sludge	Preheated Sludge	Reactor Feed	Reactor Effluent	Partially Cooled Effluent	Cooled Effluent
Parameter:								
Temperature, C	25	200	200	444	650	650	296	40
Pressure, psia	14.7	3400	3400	3400	3400	3400	3400	3400
Mass flow, kg/s	1.8	0.2	1.6	1.6	1.6	1.6	1.6	1.6
Heat flow, MW	0.0	0.0	1.1	2.7	0.94	0.0	-2.71	-1.3
Solids, kg/s	0.42	0.10	0.32	0.32	0.32	0.00	0.00	0.00
H ₂ O, kg/s	1.36	0.10	1.26	1.26	1.26	1.08	1.08	1.08
H ₂ , kg/s	0.00	0.00	0.00	0.00	0.00	0.03	0.03	0.03
CO, kg/s	0.00	0.00	0.00	0.00	0.00	0.02	0.02	0.02
CO ₂ , kg/s	0.00	0.00	0.00	0.00	0.00	0.40	0.40	0.40
CH ₄ , kg/s	0.00	0.00	0.00	0.00	0.00	0.04	0.04	0.04

Stream No.	9	10	11	12	13	14	15	16	17
Stream Name	Liquid + Solid Effluent	High Pressure Gas	Medium Pressure Gas	Mem- brane Fuel Gas	Mem- brane H ₂	PSA Fuel Gas	Mixed Fuel Gas	PSA H ₂	Storage H ₂
Parameter:									
Temperature, C	40	40	25	25	25	25	25	25	25
Pressure, psia	3400	3400	1950	20	500	20	20	500	200
Mass flow, kg/s	1.2	0.4	0.4	0.3	0.2	0.2	0.4	0.0	0.0
Heat flow, MW	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Solids, kg/s	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
H ₂ O, kg/s	1.08	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
H ₂ , kg/s	0.00	0.03	0.03	0.00	0.03	0.01	0.01	0.02	0.02
CO, kg/s	0.00	0.02	0.02	0.01	0.01	0.01	0.02	0.00	0.00
CO ₂ , kg/s	0.06	0.34	0.34	0.20	0.13	0.13	0.34	0.00	0.00
CH ₄ , kg/s	0.00	0.04	0.04	0.03	0.00	0.00	0.04	0.00	0.00

Table II-2. SCWG M&EB for 40 wt% Sewage Sludge Feed (27 MT/day)

Stream No.	1	2	3	4	5	6	7	8
Stream Name	Sewage sludge Feed	Liquefier Ash Purge	Liquefier Sludge	Preheated Sludge	Reactor Feed	Reactor Effluent	Partially Cooled Effluent	Cooled Effluent
Parameter:								
Temperature, C	25	200	200	372	650	650	383	40
Pressure, psia	14.7	3400	3400	3400	3400	3400	3400	3400
Mass flow, kg/s	1.0	0.2	0.8	0.8	0.8	0.8	0.8	0.8
Heat flow, MW	0.0	0.0	0.5	0.5	0.94	0.0	-0.52	-0.8
Solids, kg/s	0.42	0.10	0.32	0.32	0.32	0.00	0.00	0.00
H ₂ O, kg/s	0.57	0.10	0.47	0.47	0.47	0.30	0.30	0.30
H ₂ , kg/s	0.00	0.00	0.00	0.00	0.00	0.03	0.03	0.03
CO, kg/s	0.00	0.00	0.00	0.00	0.00	0.02	0.02	0.02
CO ₂ , kg/s	0.00	0.00	0.00	0.00	0.00	0.40	0.40	0.40
CH ₄ , kg/s	0.00	0.00	0.00	0.00	0.00	0.04	0.04	0.04

Stream No.	9	10	11	12	13	14	15	16	17
Stream Name	Liquid + Solid Effluent	High Pressure Gas	Medium Pressure Gas	Mem- brane Fuel Gas	Mem- brane H ₂	PSA Fuel Gas	Mixed Fuel Gas	PSA H ₂	Storage H ₂
Parameter:									
Temperature, C	40	40	25	25	25	25	25	25	25
Pressure, psia	3400	3400	1950	20	500	20	20	500	200
Mass flow, kg/s	0.3	0.5	0.5	0.3	0.2	0.2	0.4	0.0	0.0
Heat flow, MW	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Solids, kg/s	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
H ₂ O, kg/s	0.30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
H ₂ , kg/s	0.00	0.03	0.03	0.00	0.03	0.01	0.01	0.02	0.02
CO, kg/s	0.00	0.02	0.02	0.01	0.01	0.01	0.02	0.00	0.00
CO ₂ , kg/s	0.02	0.38	0.38	0.23	0.15	0.15	0.38	0.00	0.00
CH ₄ , kg/s	0.00	0.04	0.04	0.03	0.00	0.00	0.04	0.00	0.00

- Heat capacity of nonaqueous constituents approximated as 1 J/g/K (Handbook of Chemistry and Physics).
- Gas-fired heater transfers 30% of its enthalpy to the feed stream (Perry's Handbook).
- Steam generation reduces the temperature of the reactor effluent and trim heater off gas to 40°C (Mann, 1995).
- Aqueous solubility of CO₂ in the vapor/liquid separator reported by Weibe (1941).

The results of the M&EB calculations indicate that hydrogen production per unit of dry sewage sludge remains essentially constant for the two feedstock concentrations. However, use of the 40 wt% feed stream results in a significantly lower plant capital cost (see the business plan in Sec. III.A.3). Because of this, evaluation of the 20 wt% feed was dropped from further consideration and attention was directed to developing the feed concentration system.

A comparison of the M&EB results in Appendix A with the BCL gasifier (Mann, 1995) is presented in Table II-3. Note that comparable yields are achieved in hydrogen and excess process steam. The quality of the SCWG excess steam at 8.28 MPa (1200 psi) is considerably better than for the BCL gasifier at 3.45 and 0.60 MPa (500 and 100 psi), which should translate into better overall economics for the SCWG system. These considerations are discussed further in terms of process costs in Sec. III.C, business plan evaluation. However, it is clear from the comparison in Table II-3 that SCWG gasifiers should be competitive with other gasifiers currently under development.

Table II-3. Comparison of SCWG with the BCL Gasifier

Parameter	SCWG	BCL Gasifier
Plant Capacity, MT/day	27	27
Hydrogen Yield, kg/kg feed	21,863	21,600
Excess Steam, kg steam/kg dry biomass	2.82	2.98
Annual Operating Costs (without feed credit) ⁽¹⁾ , \$	(774,000)	(415,000)
Operating Costs (with feed credit), \$	(1,665,000)	—
Capital Cost of Nth Plant, \$M	6.1	5.0

¹ Includes credit for sale of hydrogen at \$10/GJ

II.B DEVELOPMENT OF COMPONENTS

A variety of separate process steps and components comprise the integrated SCWG system. The current development status of each, based on a literature review, contacts with vendors, and related SCWO/SCWG experience, is described below. Also presented is the accompanying technology development requirements needed to field a commercial SCWG

system. The specific requirements for the core SCWG process (sewage sludge size reduction, blending, and liquefying; pressurization and feeding; gasification; and pressure letdown) were defined following analysis of the four pilot-scale tests performed at GA with sewage sludge (see Appendix B).

II.B.1 Development Status of Components

This section describes the properties of sewage sludge and the manner in which they are collected and treated. It serves as a prelude to the discussion of the developmental status of each major step in the SCWG process, including pretreatment, gasification, hydrogen separation, and hydrogen storage and end use.

Sewage sludge Generation. Most municipalities within the U.S. generate both primary and secondary sludges during the handling of sewage. The process schematic for the Encina Wastewater Authority plant, located in Carlsbad, CA, shown in Fig. II-3 includes process steps that are representative of many such facilities. In primary treatment, wastewater first passes through a screen that filters out large debris. It then passes through a grit removal chamber, a long, shallow trough in which dense particles such as sand and clay settle to the bottom. After passing through the screen and grit chamber, the process stream is directed into a primary sedimentation tank, where suspended material settles out to form primary sludge and grease floats to the surface and is skimmed off. The wastewater then undergoes secondary treatment. In a typical process, the wastewater from the primary sedimentation tank is directed to an activated-sludge tank where aeration is provided to stimulate bacterial growth. The resultant bacteria-rich sludge is called activated sludge. Bacteria break down organics present in the water, which then flows to a secondary sedimentation tank. Some of this activated sludge is recycled to the aeration step to stimulate continuous bacterial growth. The remainder of the activated sludge that settles to the bottom of this tank is known as waste activated sludge or secondary sludge. Mixed primary and secondary sludge is typically about 6 wt% solids, with the sludge solids containing approximately 25% noncombustibles, primarily sand and clay. Table II-4 shows a typical composition for the combustible portion of primary sludge, along with the compositions of corn starch and woody biomass for comparison. Note that the mole ratios of carbon and hydrogen with respect to oxygen are higher for sewage sludge than for woody biomass. Thus, higher yields of hydrogen should be possible with sewage sludge combustibles than with woody biomass.

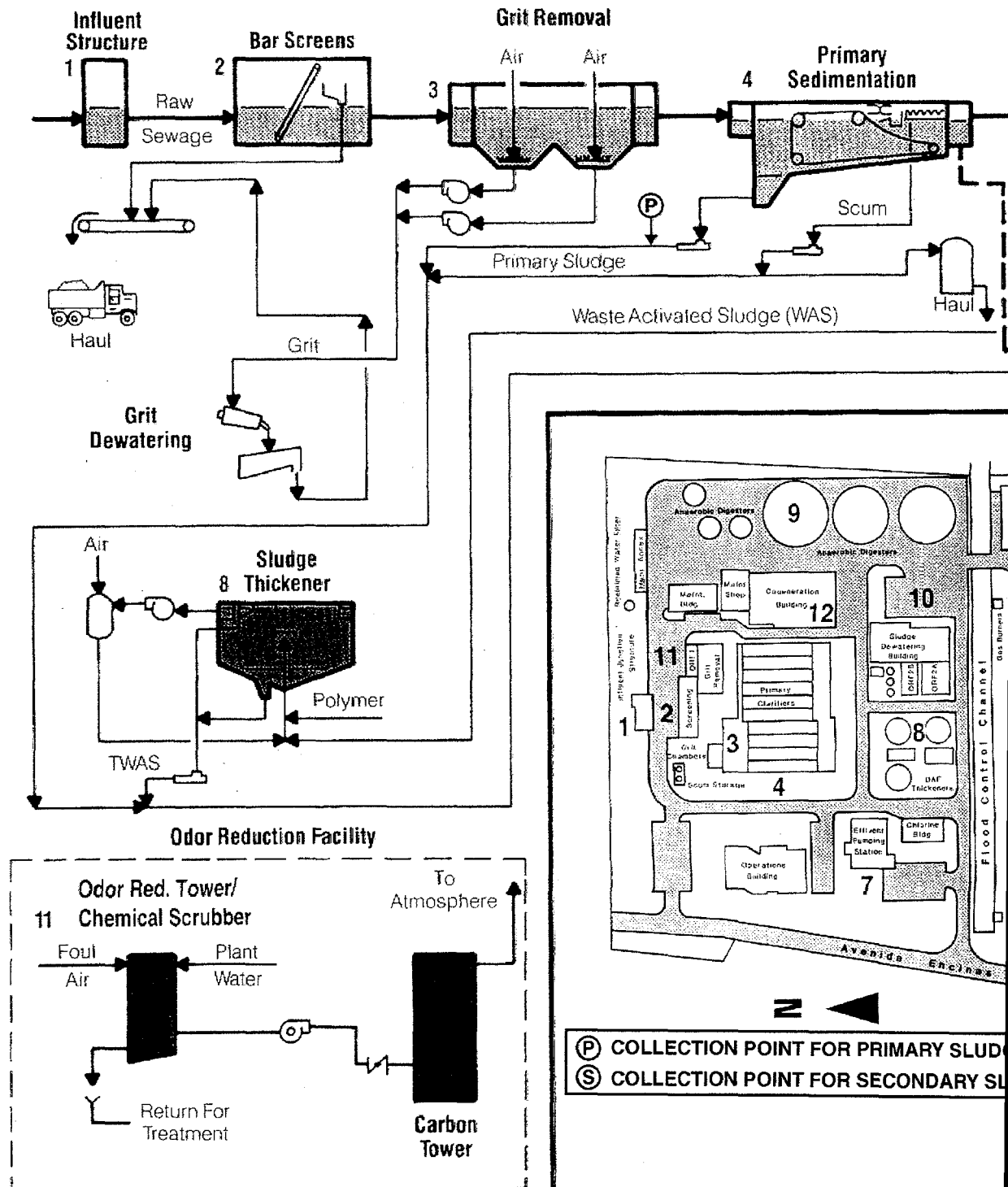
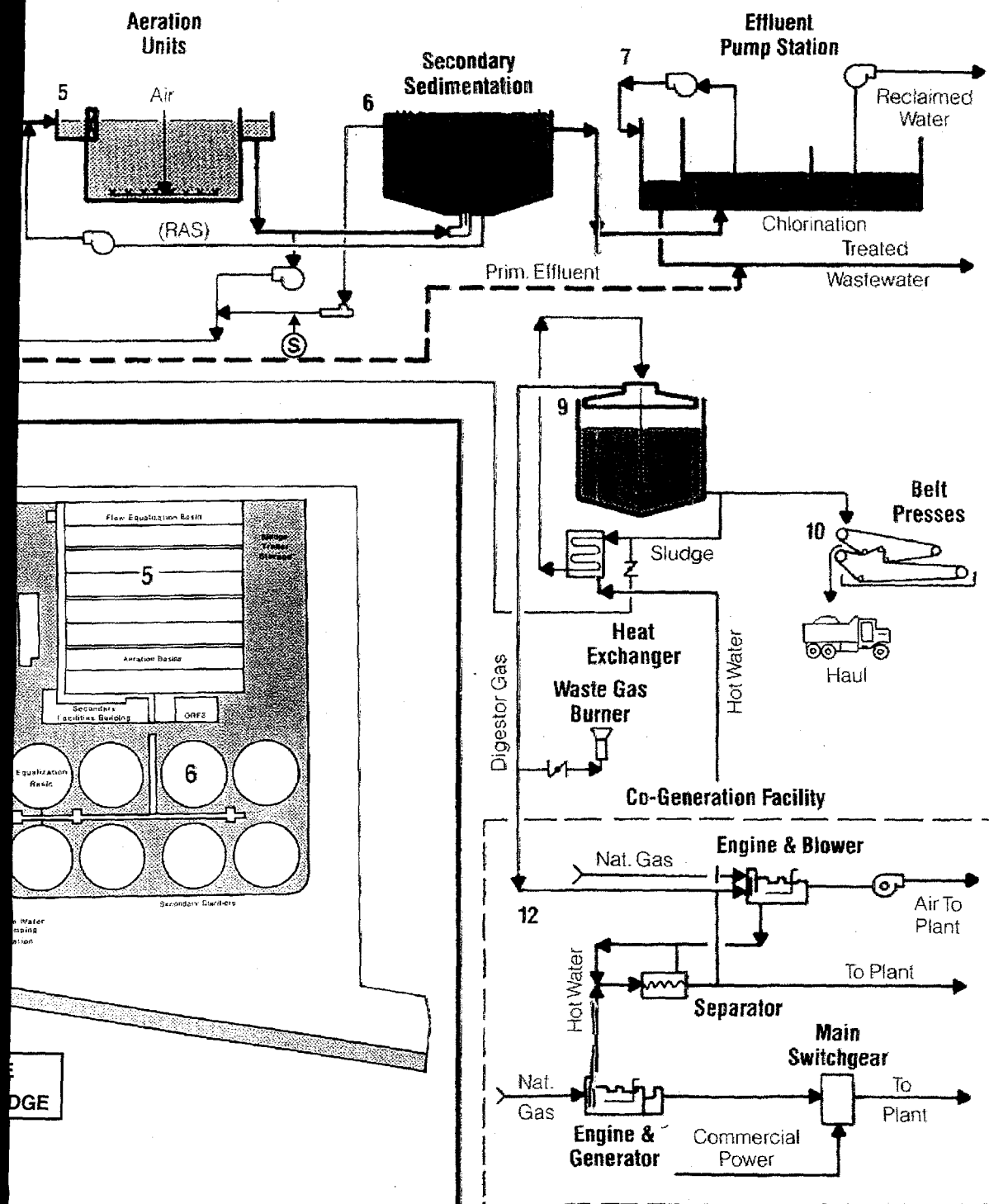


Fig. II-3. ENCINA PROCESS



CHEMATIC AND SITE PLAN

Table II-4. Composition of Combustibles in Biomass Materials

Element	Primary Sludge ^(a)		Corn Starch ^(b)		Woody Biomass ^(c)	
	Wt %	Mole ratio	Wt %	Mole ratio	Wt %	Mole ratio
Carbon	41.0	2.3	41.1	1.0	50.9	1.6
Hydrogen	5.9	4.0	6.5	2.0	6.0	2.3
Oxygen	24.0	1.0	52.4	1.0	41.9	1.0
Nitrogen	3.4	0.2	0.0	0.0	0.2	0.0
Sulfur	0.8	0.0	0.0	0.0	0.1	0.0
Ash	25	-	0.0	-	0.9	-

References:

a - McMahon et al., 1990.

b - Xu and Antal, 1997

c - Mann, 1995

With conventional sewage sludge practices at municipal installations, the primary and secondary sludges from sedimentation tanks are sent through an anaerobic digester, where they are partially metabolized by bacteria, producing CO₂, CH₄ and other by-products. Any combustible gases may then be collected and used to generate heat for the digestion tanks and buildings, and to fuel gas engines for power generation in the plant. The treated sewage sludge may also be buried or dumped as landfill, incinerated, or dried in sludge drying beds for use in land amendment. These steps are eliminated when the sludge is processed by SCWG.

Sewage Sludge Concentration. Biosolids from municipal wastewater treatment works can be treated via SCWG in the as-received concentration, i.e., ~6 wt% solids. By mixing sewage sludge with dewatering polymers, concentrations of over 10 wt% can be readily achieved (see Appendix B). However, it is cost effective to use a pretreatment step to dewater the sewage sludge prior to their introduction to the SCWG system. This arises from the more compact gasification equipment that can be used with higher feed concentrations. Conventional processes for dewatering sewage sludge include belt press filtration and screw press filtration, which yield final solids contents of up to 35 wt% and 45 wt%, respectively (Modell, 1990). These solids, in turn, can be augered into the heated, high pressure SCWG feed pump for liquefaction and ash separation.

A process similar to that described by McMahon, et al., (1990, 1991) is proposed for further sewage sludge concentration and liquefaction. In the McMahon process, mixed primary and secondary sewage sludge is hydrothermally treated at temperatures between 93 and 315°C and pressures of 1.0 to 1.5 MPa for 15 min to 2 hr. As a result, pumpable liquefied sludge at concentrations up to 50 wt% solids can be achieved. We plan to heat and liquefy

highly concentrated sludge at pressures up to 23.4 MPa (3400 psi) and temperatures of about 350°C to enable pumping and solid phase ash separation.

A closely related technology has been developed by Dr. S. Y. Yokoyama (Yokoyama 1997) and is reportedly being used commercially used in Japan to convert sewage sludge into pumpable liquid fuel.

Sewage Sludge Pumping. Hydrothermal treatment as described above has the potential to generate highly concentrated, pumpable slurries of sewage sludge. An alternative approach has been suggested by Xu and Antal (1997), in which a mixture of corn starch and sludge solids creates a pumpable mixture. To date, the highest pumpable concentration that has been formulated contained 7.7 wt% each of corn starch and sewage sludge. A drawback of this approach is that purchase of corn starch could be prohibitively expensive. However, a feed additive may be required for other biomass feeds that are perhaps less easily liquefied than sewage sludge.

One method of pumping liquefied biomass utilizes a piston-in-cylinder design such as used in the cement industry. Industrially, such pumps are typically operated at fairly low pressure, e.g., 1.2 MPa (175 psi). A high pressure piston-cylinder design was utilized by Hong, et al., (1996) to pump 20 wt% corn flakes in a laboratory-prototype SCWO unit built for NASA. Xu and Antal (1997) used a piston-cylinder type pump to deliver the 15% slurry of 50/50 corn starch and sewage sludge mentioned above.

A second method for pumping difficult slurries utilizes cylindrical diaphragm pumps. The feed material is introduced to the inside of a cylindrical elastomeric tube at low pressure. The outside of the tube is then pressurized with a clean hydraulic fluid to force the feed from the tube. Zimpro Environmental is the leader in this field, having developed this type of pump for feeding thick slurries including sewage sludge to a treatment process known as wet air oxidation. Wet air oxidation is the precursor technology to SCWO, effecting oxidation in an aqueous environment at temperatures up to about 350°C and pressures up to about 27.5 MPa (4000 psi). Cylindrical diaphragm pumps have been used to pump particulate material over 5 mm in diameter.

SCWG Heat Recovery Heat Exchanger. The properties of the SCWG feed favor a simple flow path. For similar feeds, double-pipe heat exchangers have typically been used, with the feed material flowing in the inner pipe. This design was tested in the GA pilot plant SCWO tests at sewage sludge concentrations up to ~10 wt%. A similar design is envisioned for SCWG systems and is available as commercial units.

SCWG Gas-fired Trim Heater. The SCWG trim heater is used to bring the feed stream to the final reaction temperature of about 650°C. Gas-fired heaters are commercially available in the sizes required for SCWG systems. External electrical heaters have been successfully used in the GA pilot-scale testing with sewage sludge for preheating up to 650°C while internal electrical heating has been successfully used in the lab by Xu and Antal (1997) to heat sewage sludge-corn starch mixtures up to 650°C. Commercial-scale gas-fired heaters were developed for a new SCWO system by Foster-Wheeler installed at Pine Bluff Army Ammunition Plant in Arkansas.

SCWG Reactor. Table II-5 provides a brief comparison of existing high-pressure, high-temperature reactors relevant to SCWG. All are vessel-type reactors that are amenable to low-face-velocity flow through a packed bed of catalyst. The table shows that suitable reactor fabrication technology exists for even very large SCWG gasifier plants. In particular, ammonia synthesis is a highly mature technology with similar temperature and pressure requirements. Other notable features of ammonia synthesis reactors include a packed bed of catalyst and active cooling of the vessel walls by cold incoming feed (Barnes and Oh, 1994).

Table II-5. Fabricated Reactors Relevant to the SCWG Process

Application	Max T (°C)	Max P (MPa)	ID (cm)	Volume (L)	Ref.
GA SCW Pilot Plant	650	25.0	10	18	-
GA Navy SCWO	650	25.0	18	40	-
GA/MODAR SCWO	650	23.5	25	110	-
Zimpro wet oxidation	300	15.0	183	48,000	a
Ammonia synthesis	550	30.0	300	190,000	b
Texaco coal gasifier	1370	17.5	270	26,000	b

References:

a - Zimmermann, 1958

b - Barnes and Oh, 1994

SCWG Catalysts. The most effective catalyst identified to date is GAC as utilized by Antal (1996), which has afforded nearly total gasification of a number of feedstocks in laboratory-scale testing. Other catalysts that have been suggested for SCWG include nickel, molybdenum, cobalt, and their oxides or sulfides; noble metal catalysts such as platinum or palladium (Modell et al., 1978); nickel or cobalt in combination with alkali metal carbonates (Sealock, Jr. and Elliott, 1991); ruthenium, rhodium, osmium and iridium (Elliott, et al., 1997); and compositions containing iron oxide or zeolites (Sealock, Jr., et al., 1997).

Table II-6 provides a comparison of experimental data for activated carbon and the most effective alternative catalysts tested to date. Weight hourly space velocity (WHSV) presented in Table II-6 is defined as the ratio of the mass flow rate of the feed to the mass of catalyst (Xu, et al., 1996) and is a measure of catalyst efficiency. As indicated in Table II-6, activated carbon has shown far higher hydrogen yields than other catalysts. However, the other catalysts have been tested under far different conditions. Xu and Antal (1997) have noted that the product spectrum in their GAC tests did not vary greatly with WHSV, suggesting that the high yield of hydrogen is a near-equilibrium composition. If this is true, then other catalysts may be able to achieve a comparable product spectrum at similar temperatures. Antal is currently performing DOE-sponsored work to evaluate catalysts other than GAC.

Table II-6. Catalyst Performance Comparison²

Catalyst	Feed (wt%)	Test Time (hr)	T (°C)	P (MPa)	WHSV ^(a)	% Gasified	Mol % H ₂	Ref
Coconut shell GAC	10.4% Starch	6	650	28.0	3.0	99.6	47	b
Coconut shell GAC	5.1% Starch + 2.1% biosolids	2	650	28.0	1.5	99.7	43	b
Coconut shell GAC	17% Glucose	NA	600	34.5	13.5	98	27	c
Coconut shell GAC	17% Glucose	NA	550	34.5	13.5	54	17	c
Coconut shell GAC	17% Glucose	NA	500	34.5	13.5	51	14	c
5% Ru on Al ₂ O ₃	10% Cresol	240	350	20.7	0.8	95.0	1.2	d
Ni 1404	10% Glucose	1	350	23.4	0.8	97.7	5.6	e

Notes:

a - WHSV: Weight hourly space velocity

b - Xu and Antal, 1997

c - Xu et al., 1996

d - Elliott et al., 1997

e - Sealock, Jr. et al., 1997

² Antal points out that they have usually observed the following gas composition from sewage sludge blended with cornstarch: 43% H₂, 39% CO₂, 17% CH₄, and 1% CO, and that different sewage sludges behave differently in a catalytic SCWG system. Antal further cautions that it may not be possible to produce the same gas composition from gasified sewage sludge as achieved for sawdust and corn starch. While our assumed gasification yields may be optimistic, the overall process economics for SCWG are fairly insensitive to the range of gas compositions from 43% H₂ to 53% H₂ yield, such that the overall conclusions are not affected.

SCWG Byproduct Steam Generation. Byproduct steam is generated in two locations with the SCWG PFD (Fig. II-2): from the waste heat boiler during the final effluent cooldown and from the gas-fired trim heater flue gas. The latter is a common application and should be readily addressed by conventional technology. Cooldown of an effluent from SCWG is a less common operation, but has ample precedence in the wet oxidation field as well as in other gasification technologies. For this reason, this unit operation is considered to be fully developed.

SCWG Gas-Liquid Separation. SCWG inherently incorporates a scrubbing step as the process stream is cooled downstream of the reactor and the water condenses. The gas stream leaving the gas/liquid separator will contain only trace amounts of liquid droplets, solid particulates, and dissolved solids. Depending upon the particular feedstock, product gas from biomass gasification may also contain the following gaseous constituents at more than trace levels:

- Acidic: H_2S , CO_2
- Neutral: CO , H_2O , N_2 , CH_4 , C_xH_y
- Basic: NH_3

Water droplets and NH_3 should only be present at low levels, being largely trapped in the aqueous phase in the gas/liquid separator. Furthermore, for most biomass feedstocks, NH_3 would be trapped in the form of NH_4HCO_3 in the aqueous phase.

Gas liquid separation at full system pressure, as shown in Fig II-2, was practiced for many years at MODAR, Inc., and is a commercially ready unit operation.

Membranes for Hydrogen Purification. Gas separation via the use of membranes is based on the principle of selective permeation, whereby each gas constituent has a characteristic permeation rate that is a function of its ability to dissolve and diffuse through a membrane (Michael, 1997). Polymer membranes have been used to produce medium purity hydrogen since the early 1970's. The membranes are typically comprised of aromatic polyaramide, polyimide, polysulfone, or cellulose acetate, packaged as spiral-wound sheet or hollow fiber membrane cartridges (Kroschwitz, 1995, Elvers, 1989). Hollow fiber membrane cartridges are currently in use for industrial hydrogen purification at pressures up to and exceeding 70.0 MPa (10,000 psi). For common practice, however, a typical maximum pressure is about 17.0 MPa (2500 psi) (Wilcher, et al., 1995). Membrane modules must sometimes be preceded by scrubbing systems to avoid chemical degradation from substances such as NH_3 , H_2S , or

CH₃OH. This will likely not be required by SCWG systems due to the inherent scrubbing action of the process. Membrane selectivity has been previously described in conjunction with Fig. II-2.

Pressure Swing Adsorption for Hydrogen Purification. PSA is well-suited to the production of high purity hydrogen because of the high selectivity differences between hydrogen and other components on typical adsorbents. Common adsorbents used in hydrogen PSA systems include alumina, silica gel, zeolites and activated carbon (Golden, 1997). Feed to the unit must contain at least 70% hydrogen. Gas purification is accomplished by adiabatic adsorption of contaminants at high pressure at about 3.45 MPa (500 psig), followed by depressurization and purging of the contaminants with clean product gas at about 137 kPa (20 psig). PSA can also be used to remove major impurities such as H₂O, O₂, N₂, CO₂, and CO from a hydrogen-containing stream. Hydrogen leaving a PSA unit has a purity of approximately 99.9% and will contain only a few ppm of impurities such as H₂O, CO, CO₂, and CH₄. Hydrogen recoveries are in the range of 80 to 92% at essentially feed pressure (Miller and Stoecker, 1989). The PSA process has been in commercial use since the 1960's.

Hydrogen Storage. The present SCWG integrated system poses no special requirements for hydrogen storage, so only currently mature technologies have been considered, including compressed gas and liquid storage. Gaseous hydrogen is stored at high pressure in steel cylinders at 15.0 MPa (2200 psi) to 40.0 MPa (5800 psi) (Kroschwitz, 1995). Small quantities are supplied in 70 L cylinders, while larger quantities are supplied in tube trailers about 20 m³ in size. Low pressure spherical vessels are also used, containing about 15,000 m³ of gas at up to 1.6 MPa (230 psi). The latter has been depicted in Fig. II-2, and would hold about 3 days of production from a 27 MT/day plant. Low pressure gas storage has been selected for the SCWG unit because no compression is required for the product gas leaving the PSA unit. Low pressure gas storage is also compatible with final usage technologies such as fuel cells and advanced gas turbines.

Liquid hydrogen is used in the various international space programs and also as a storage means in industry. It has been proposed for future use as aircraft and ground vehicle fuel. Liquid hydrogen is stored at -253°C (20K) and ambient pressure. Purified gaseous hydrogen is first cooled to -40°C using liquid ammonia heat exchangers and then to -196°C using a liquid nitrogen bath. Once liquid nitrogen temperature is achieved, the hydrogen is purified with activated carbon, which reduces contaminant levels (e.g., H₂O, CO, CO₂, and CH₄) to less than 1 ppm. The final stage of liquefaction is achieved using a Joule-Thomson valve. Current technology requires about 13.4 kWh/kg to liquefy hydrogen (Pelloux-Gervais, 1995), equivalent to about 40% of its higher heating value.

Molecular hydrogen is comprised of two forms known as ortho, in which the nuclear spins of the two atoms are parallel, and para, in which the nuclear spins of the two atoms are antiparallel (Kroschwitz, 1995). At ambient temperature, hydrogen is 75% ortho and 25% para, while stable liquid hydrogen at near ambient pressure is in contrast 99.8% para. Catalyst beds are utilized during the liquefaction procedure to effect the exothermic conversion from ortho to para, which is otherwise slow and could lead to storage tank overpressurization or excessive vaporization.

Loss due to vaporization is an important factor in cryogenic storage. A 70,000 gal double wall tank with a high vacuum annulus loses about 0.3% of its contents per day. Typical losses for a 10,000 gal tank truck are about 2% per day (Buchner, 1995). In addition to the usual concerns of hydrogen compatibility, cryogenic compatibility must also be addressed in materials selection. Because of these issues, cryogenic storage of SCWG-generated H₂ was dropped from further consideration.

Numerous alternative techniques have been suggested as methods for hydrogen storage, for example, cryoadsorption on activated carbon (Hynek, et al., 1994) or carbon nanotubes (Dillon et al., 1995), and high temperature adsorption on zeolites (Weitkamp, et al. 1995). Another approach that has received a great deal of attention is the use of metal hydride systems, of which variations abound (Kroschwitz, 1995). A primary objective of most of these techniques is a user-friendly storage method suitable for everyday transportation needs. None of these alternative techniques has yet achieved commercial significance, and most require substantial further development.

Final Usage of SCWG Hydrogen Product. An obvious alternative for usage of the hydrogen produced by the SCWG plant is over-the-fence sales to other industries. Unless the purchasing party is close at hand, however, this alternative would require compression or liquefaction of the product stream from the PSA unit. One use of hydrogen that could be favorably employed on site, and thus not require reduction in volume for transportation, is fuel cells. Fuel cells offer the potential for greater than 70% efficiency and up to ten-fold reductions in equipment footprint for electric power generation versus conventional systems. Table II-7 summarizes the different types of fuel cells that are currently commercially available or near-commercial. Present development activity is focused on medium to high temperature technologies because the waste heat from these units can be used for preprocessing the feedstock. Preprocessing allows a wide variety of materials to be used as fuels by being converted in situ to hydrogen. The alkaline fuel cell, which operates at low temperature and requires pure hydrogen, is the most highly developed, being used extensively in the U.S. and European space programs. As pure

hydrogen becomes widely available, low temperature fuel cells are likely to become more generally applicable.

Table II-7. Commercial and Near-Commercial Fuel Cells

Type	Available Size (MW)	Optimum Temperature (°C)	Feed Gases	Ref.
Alkaline	<<1	<80	Pure H ₂ and CO ₂ -free O ₂	a, c
Phosphoric Acid	11	200	H ₂ , H ₂ /CO mixtures	b
Proton Exchange Membrane	0.25	95	Pure H ₂	c
Molten Carbonate	2	650	CH ₄ , HCs, H ₂ /CO ₂ and air	d
Solid Oxide	4	1000	H ₂ and/or CH ₄ and air	e

Notes:

a - Kordesch and Olivera, 1988

b - Sinor, 1989

c - Appleby, 1992

d - Energy Research Corporation web site, www.erc.com, 10/97

e - Parker and Bevc, 1995; Westinghouse Science and Technology Center web site, www.stc.westinghouse.com, 10/97

A second alternative for on-site use of hydrogen is the use of a hydrogen-fueled combustion turbine cycle. Such cycles are being developed both to advance the efficiency of power generation as well as to meet the environmental compatibility goals of the hydrogen economy. Bannister, et al. (1996a) have indicated that a hydrogen-fueled direct-fired Rankine cycle should be able to attain 70% lower heating value thermal efficiency by about the year 2020. By comparison, current-day natural gas-fired combined cycles have a maximum thermal efficiency of about 55% (Bannister and Newby, 1996b). Another nearer-term alternative for achieving the benchmark of 70% lower heating value thermal efficiency utilizes a combination of a pressurized solid oxide fuel cell followed by a commercially available gas turbine. A plant of this type generating 3 MW of electricity is expected to be operational by the year 2000 (Parker and Bevc, 1995).

For the first commercial installation of an SCWG integrated plant, it is desirable to minimize the technical risk and capital expense of the affiliated non-core technologies. For this reason, a fuel cell system of approximately 2.4 MW capacity for the 27 MT/day system, with an efficiency approaching 55%, is more suitable than a hydrogen-fueled turbine or a combined fuel cell-gas turbine system. Hydrogen usage for subsequent installations should be reevaluated in light of the advancing state of the art.

II.B.2 Technology Development Requirements for Components

Each of the process steps in SCWG is in commercial or near-commercial operation. Nonetheless, a number of technology development issues warrant study to ensure effective integration of the entire system. This section describes technology development requirements to be addressed during Phases II through IV of the program.

Sewage Sludge Pretreatment. Sludge concentration is a necessity for the economic viability of SCWG. Achievement of suitably high concentrations in a pumpable form requires alteration of the properties of the as-received sewage sludge. While various types of chemical or biological treatment have been considered, physical heat treatment has been chosen. Toward this end, the hydrothermal concentration/liquefaction techniques, including those suggested in the patent literature (McMahon, et al. 1990, 1991), need to be further tested and verified. Ash segregation in the pressurized sewage sludge liquifier also needs to be demonstrated since high ash contents in sewage sludge carry a significant penalty in terms of equipment size and design.

Another consideration in sewage sludge pretreatment is size reduction of the feed material to allow reliable pumping and smooth reactor operation. Batch-process maceration of blended primary and secondary sludges was performed during pilot plant testing at GA (See Appendix B). Size reduction is best carried out before concentration, while the sludge can be easily pumped. It is possible that the conventional processing that sewage sludge receive at the wastewater treatment facility plus hydrothermal pretreatment will provide sufficient size reduction, but this requires testing.

Sewage Sludge Pumping. Pumps that can handle extremely thick pastes are commercially available, for example the piston-cylinder or cylindrical diaphragm type pumps previously mentioned. Another possibility is a progressive cavity pump, which is used industrially for moving materials such as peanut butter. The spiral-like motion of this type of pump may, however, be susceptible to fibrous materials such as cellulose and hair that are found in sewage sludge. Pumps of each type have been built for the high pressures encountered in the SCWG process. An important aspect of the planned pump testing will be inclusion of pump heating to liquefy the feed before it is pressurized to SCWG feed conditions.

SCWG Heat Recovery Heat Exchange. The starting point for heat exchanger design is the commercial-scale double-pipe configuration utilized by Zimpro Environmental, which has been successfully utilized for many years in numerous plants treating sewage sludge by wet air oxidation. A double-pipe heat exchanger has also been used in GA pilot plant testing, although only at the relatively low feed concentration of 10 wt% (see App. C). Operation was satisfactory,

although the maximum duration of approximately 8 hr during SCWO testing was insufficient to ascertain long-term viability. It should be demonstrated that the double pipe configuration is suitable for very thick slurries, as the required pipe length could conceivably result in undesirably high pressure drops.

A common concern when carrying out heat exchange with high salts-content feed is precipitation of inverse solubility salts, i.e., salts whose solubility decreases with increasing temperature. The chief example is CaSO_4 , although other alkaline earth salts can behave in a similar manner. Some wet air oxidation plants must shut down on a weekly or biweekly basis to flush components with dilute acid to remove scale. Fortunately, the sewage sludge pretreatment processes described above will likely remove most of the inverse solubility salts prior to their introduction into the gasifier and heat exchanger, minimizing this concern. However, this needs to be demonstrated during pilot-scale testing.

A second concern is the possible formation of organic chars. The relatively slow feed heatup that occurs within the heat exchanger may lead to organic tar formation. Xu, et al., (1996) report that swirling feed introduction in the heatup zone of their reactor is useful in mitigating tar formation and extending catalyst life. Thus rapid heatup of the feedstock appears to be important in order to minimize condensation reactions. For some feedstocks, char formation may be mitigated by the addition of a small quantity of oxidant to the stream being heated.

Optimum materials selection also requires investigation. Titanium has proven to be highly useful for corrosion resistance in the SCWO process, even at temperatures hundreds of degrees Celsius above its maximum rating in the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code. It has also proven to have exceptional corrosion resistance in commercial wet air oxidation systems, although the addition of small amounts of oxygen to the feed stream is sometimes needed to allow maintenance of the passivated oxide layer on the metal. Furthermore, the stability of titanium decreases as temperatures increase above about 350°C.

SCWG Gas-fired Trim Heater. Development requirements here are essentially the same as for the heat recovery heat exchanger. Conditions are more extreme in some respects, however, with some high pressure piping being exposed to flame or near-flame temperatures. As such, the trim heater operates with a higher temperature feed stream and presents a further opportunity for organic or inorganic scaling. At trim heater temperatures, even highly soluble alkaline salts such as NaCl and Na_2SO_4 may precipitate, potentially degrading heater

performance and causing hot spots that can lead to tube failure. The relatively low concentration and limited duration of both the lab and pilot testing suggest the need for further testing of the proposed flow scheme. Firing of the heater with the hydrogen-depleted off gas is not expected to present any significant difficulties.

With regard to feed preheating, a backup option of partial oxidation may be considered. In this flow scheme, cold feed is introduced directly into the reactor, where it is rapidly heated by mixing with the existing contents of the reactor. The slow heatup problem is thus avoided in this scenario. Upon achieving sufficient temperature, the feed reacts with oxidant that has been supplied to the reactor, partially oxidizing and generating a self-sufficient amount of heat. Partial oxidation for providing heat is used in many commercial gasifiers, e.g., the Texaco gasifier. Initially, a rough economic estimate will be made to clarify the tradeoffs involved in supplying high pressure oxidant to the system, thereby simplifying the design of the heat recovery heat exchanger, the gas-fired heater, and the delivery of feed to the reactor (no requirement to force feed through long lengths of small diameter pipes) versus the baseline approach. It is anticipated that the economic estimates will show that the baseline PFD is favored. If, however, the heat exchanger and heater designs with liquefied feed prove to be especially difficult, the partial oxidation option is a leading alternative.

SCWG Catalysts. In the scale-up testing performed at GA during Phase I, a possible drawback of GAC catalyst - its relatively low physical strength - was noted. The GA tests utilized a vertical, down-flow reactor with a catalyst bed height of approximately 0.5 m. The downflow design likely exacerbated the effects of pressure variation, leading to GAC degradation. Use of an upflow reactor design, as shown in Fig. II-2, is expected to markedly reduce this effect. Another possible cause of degradation in the pilot plant tests may have been the cylindrical shape of the graphite catalyst used, with accompanying sharp edges that are prone to fracture. The use of more spherically shaped particles, as tested by Antal, would further help to diminish this concern.

Catalysts other than GAC also need to be tested at temperatures of 600°C and higher and at representative pressures. The ideal catalyst will have high processing rates (WHSV), effect essentially complete gasification, and provide a high hydrogen yield. GAC and potential alternative catalysts also need to be tested for long-term durability under SCWG conditions. This includes resistance to crushing, poisoning and sintering.

Tests must also be carried out without catalysts to ascertain the tradeoffs involved. For example, a somewhat higher temperature of operation may provide equivalent gas yields.

Catalysts that provide only marginal yield improvements or that introduce numerous practical problems may not be worth the added complications they may introduce.

SCWG Reactor. The SCWG reactor is the key component in the SCWG process scheme, and presents several questions that merit further investigation. One of these is the thermal balance within the reactor, i.e., whether the overall SCWG reaction is endothermic or exothermic. The balance is affected by a number of different parameters, in particular feedstock composition and water content, and pressure and temperature of operation. Modell (1985) evaluated a model biomass gasification system for dextrose/water in a 1:5 molar ratio at 1.0 MPa (145 psi) and showed that the overall equilibrium reaction changed from exothermic to endothermic as the reaction temperature increased above about 650°C. In terms of SCWG operation, the most desirable thermal balance is probably slightly exothermic, allowing the reactor to run essentially isothermally when heat loss is accounted for. This requirement may serve as a constraint to the maximum operating temperature.

These and other analyses highlight that there is a need for chemical equilibrium calculations, validated with experimental results, to help ascertain the most desirable operating conditions for SCWG reactor³. Similar studies have been performed with sewage sludge under SCWO conditions in GA's pilot plant. Because existing commercial gasifiers operate at pressures up to about 3.5 MPa (500 psi) and temperatures from 500 to over 1000°C (Katofsky, 1993), a wide range of conditions can be modeled.

Residence time within the reactor is a key variable that will be more clearly defined by further development. For example, residence time is expected to be dependent upon the feed particle size. Velocity within the reactor may be an important variable.

Another key issue is the direction of flow in the reactor. An upflow design is being considered as a means to reduce the potential for catalyst bed crushing. Susceptibility of the bed to crushing obviously depends upon the particular catalyst employed.⁴

³ Antal points out that conditions within an SCWG reactor are not sufficiently severe to realize equilibrium, and that research is needed to better define the product spectrum as a function of various process variables.

⁴ Antal suggests that a fluidized catalytic bed may have merit, or that a hard carbon such as petroleum coke may be better at resisting crushing.

Reactor material of construction also warrants further review. Many recent SCWO reactor designs have incorporated interior chambers removed from the pressure-bearing shell, allowing the shell to operate at a significantly reduced temperature. Potential corrosion in the SCWG environment has received little study thus far. To date, many of the materials utilized in SCWO have been adopted for SCWG with good performance, but longer term data is needed.

Gas Purification. Membrane and PSA units have a low tolerance for certain contaminants such as H_2S . However, because of the inherent scrubbing action of SCWG, off gas purification is not expected to result in membrane or PSA poisoning. Thus no subsystem component testing of these units is planned for Phase III.

Fuel Cells. Significant advancements are currently being made in the fuel cell field. As the SCWG process places no special constraints on the use of this technology, discussion of required developments is considered to be outside the scope of this plan.

Summary. Table II-8 summarizes the development needs described in this section.

Table II-8. Summary of Development Requirements for Component or Subsystem Technologies

Category	Development Requirement
Sewage Sludge Pretreatment	Sewage sludge concentration Particle size reduction Sewage sludge liquefaction Ash removal
Sewage Sludge Pumping	Pump testing
Heat Exchange and Fired Heating	Operability testing Reliability testing Materials of construction testing
Catalysts	Identification of materials
Reactor Design	Thermodynamic modeling SCWG extended operations Ash behavior Residence time requirement Materials of construction testing
Gas Purification (Membranes and PSA)	None
Fuel Cells	None

II.C DEVELOPMENT OF INTEGRATED SYSTEM

The integrated SCWG system will be developed in Phases II, III and IV of the proposed program. During Phase II, Technology Development, the development requirements listed above in Table II-8 will be addressed. Initially, three parallel tasks will be pursued: sewage sludge pretreatment and pumping, alternative catalyst testing, and gasification equilibrium modeling. Sewage sludge pretreatment and pumping tests will be carried out using GA pilot-scale equipment, while catalyst testing will be performed in GA laboratory apparatus. The bulk of the laboratory work will be performed with model compounds such as glucose. Gasification equilibrium modeling will be performed using ASPEN® or an equivalent process modeling program. The modeling will explore the optimum temperature, pressure, and feed composition conditions for SCWG gasification. Laboratory testing will include a verification of optimum operating conditions and WHSV.

Once sewage sludge pretreatment and pumping have been suitably demonstrated, and preferred operating conditions and catalysts identified, the results will be implemented in a pilot plant test program. This program will involve longer duration tests than previously performed, with a target of at least 8 hr of continuous operation. As part of the pilot test program, heat exchanger and heater reliability will be monitored and measurements and observations regarding materials of construction will be carried out. Disposition and behavior of ash within the reactor will also be analyzed.

At the conclusion of Phase II, the SCWG PFD, M&EBs, and system interfaces (e.g., sewage sludge supply, vendor technologies, disposition of H₂ product) will be defined for the Phase III effort.

Phase III, Technology Validation, involves detailed design and fabrication of upgraded equipment for the pilot-scale demonstration of Phase IV. The piping and instrumentation diagram will be prepared and the process control logic developed. Equipment drawings and specifications will be prepared, equipment procured, and assembly begun. Testing of key SCWG subsystem components (e.g., sewage sludge drying, feed liquefaction and pumping, feed preheating, gasification, heat recovery, and pressure letdown) will then be performed. Supporting tasks, including a safety evaluation, RAM studies, and required permitting will be carried out. Economic estimates will also be revised to be consistent with the experience of the Phase II program to ensure that the technology continues to meet the criterion of economic viability.

Phase IV, Demonstration of Scale-Up, comprises a pilot-scale demonstration of the integrated SCWG technology. The pilot-scale unit will process about 5 MT/day of sewage sludge, approximately one-fifth the size of the smallest commercial unit envisioned. The enlarged pilot plant system will undergo shakedown testing with progressively more complex feeds. Integrated system testing with concentrated sewage sludge will then be carried out over a period of several months. A successful demonstration at this scale should be sufficient to attract municipal/industrial partners for a commercial demonstration.

II.D IDENTIFICATION OF BARRIERS AND POTENTIAL SOLUTIONS

A number of potential technical barriers have been described above in terms of technology development requirements. Assuming these requirements are met, there remain potential barriers with respect to displacement of existing technology, environmental concerns, and safety issues. These potential barriers are considered in this section.

By virtue of its long history, municipal wastewater treatment is a well-established industry. Many wastewater treatment plant operators are likely to be risk averse toward a new technology given that they have existing plants and sewage sludge disposal practices that are providing satisfactory service. To gain a better appreciation of existing practice and potential technical barriers, discussions were held with Encina personnel and other regional wastewater facility operators. The Encina plant, located approximately 10 miles north of GA, treats sewage for a population of approximately 225,000 residents (see Fig. II-3). It generates 90 to 100 MT/day of treated secondary waste at 17 to 18% solids content and pays about \$24/wet ton for hauling to Riverside county for land farming. This is a typical value for Southern California wastewater treatment facilities (Los Angeles, Orange County, San Diego).

In order to displace existing practices, SCWG will have to demonstrate among other things that it is as reliable as conventional techniques. This fact can only be established by an extensive operating history. To address this issue, it is anticipated that the first several units will be installed at existing facilities. With this approach, should technical problems be encountered or process modifications be desired, the treatment works can fall back on existing facilities and still fulfill its obligations to the community. As the SCWG technology matures, it may be considered as the sole sewage sludge handling facility in new or renovated treatment works.

There are no apparent environmental barriers to the SCWG technology. Water and solids effluents from the SCWG system will be cleaner than those resulting from conventional wastewater processing. Carbon dioxide in the flue gas is a greenhouse gas, but this carbon is already active in the global carbon cycle and does not provide any net transfer from

sequestered carbon (coal, oil, gas reservoirs, clathrates and rocks) to the atmosphere. In addition, the relatively low operating temperature results in minimal emissions of nitrogen oxides and sulfur oxides. By the same token, land application of sewage sludge is generally regarded as safe and environmentally friendly, providing fertilization, aiding reclamation of disturbed land, and avoiding water pollution (ocean dumping) and air pollution (incineration) (see the Water Environment Federation web site at www.wef.org), but requiring truck transportation and additional fossil-fueled methods to apply. Thus, while SCWG is positioned as a "green" technology, it may be appropriate to claim only modest improvements over existing methods.

A concern sometimes expressed with regard to SCW systems is the combination of elevated temperatures and pressures. However, a number of highly mature industrial technologies utilize a similar range of conditions. Comparable temperature and pressure conditions are found in thousands of power plants worldwide, as well as in the chemical processing industry where the two most common applications are ethylene polymerization and ammonia synthesis. Wet air oxidation, the forerunner of SCWO, is practiced at over 200 locations worldwide. SCWO, the sister technology of SCWG, has been under development for more than 15 years, during which time an excellent safety record has been established. It is possible that a commercial SCWO system treating a complex waste will be in operation within the next several years, lending credibility to the viability of SCW processes. Thus while there is a valid safety concern as to the SCWG operating conditions, it should be equally clear that industry has ample know-how to handle these conditions safely.

III. BUSINESS PLAN

A business plan has been developed for the commercialization of SCWG for the treatment of sewage sludge and hydrogen production. Three primary sources of data have been used in developing the plan: (1) costs and other information gathered from the technology survey, wastewater treatment facility operators, and supplier contacts; (2) GA's related experience with SCWO of sewage sludge and hazardous wastes; and (3) projection of pilot plant costs to near-commercial and commercial-scale units. After these data were acquired, key topics in the BizPlan commercial software were reviewed and the focus of each topic defined, financial projections prepared, and the business plan prepared. The following sections cover the (1) development of the business plan, (2) results and evaluation of the business plan, and (3) associated technical and financial requirements to establish a SCWG system commercial capability.⁵

III.A BUSINESS PLAN DEVELOPMENT

The SCWG business plan was developed along parallel lines used by Mann (1995) to evaluate the BCL gasifier. Throughout, the objective has been to identify engineering and economic considerations needed to achieve capital and operating costs that would be competitive with the BCL gasifier. Thus, high sludge feed concentration and economies of scale are two of the primary requirements for achieving parity with the BCL gasifier. In terms of other sources of power (fossil fuels, etc.), rising prices over the next several decades and/or carbon taxes will be needed to bring biomass-derived sources into the competitive range. These drivers are well known and are not at issue here. What is at issue with whether or not SCWG of sewage sludge (and other municipally derived or industrially generated biofuels) is a technically and economically viable method when compared to competing methods. We attempt to make this case in the following sections.

The SCWG business plan was developed using the text templates included in BizPlan Builder. The following sections describe the BizPlan Builder software and the methodology and assumptions used in developing the SCWG Business Plan.

⁵ Note that commercialization of large, centralized SCWG systems does not involve the development of manufacturing capabilities, since the appropriate industries and infrastructure are already in place for other large, capital-intensive systems such as wastewater treatment plants and power plants.

III.A.1 Description of BizPlan Builder

The commercial software BizPlan Builder published by JIAN Tools for Sales, Inc. was used to develop the plan for commercializing the SCWG integrated system. The BizPlan software incorporates a series of templates that pose key questions for analysis and provide suggested verbiage for written text based on responses to these questions. Central topics covered by the templates include Product Strategy, Market Analysis, Marketing Plan, and Financial Plan. The Financial Plan template includes spreadsheets that can be used to calculate a wide variety of financial yardsticks, including life-cycle-cost and break-even analyses, as well as supporting documents such as budgets, income statements, balance sheets and cash flows. Overall, BizPlan provides basic formats and financial analysis tools needed when defining a new business venture or activity. Tailoring of template topics was performed as a part of the business plan preparation process since each template includes topics that were not needed or appropriate for evaluation of the proposed SCWG technology. In addition, the financial template was not used since it did not allow calculations out past five years, necessary to project the long-term financial outlook for SCWG. However, a summary of labor requirements and costs associated with planned near-term development work have been included.

III.A.2 Methodology and Assumptions

Development of the plan incorporated a series of steps and associated assumptions that progressed from the definition of the optimum sizes for the commercial SCWG units through completion of the marketing and financial plans.

Step 1 - Define Optimum Size of Integrated System. Sewage sludge are produced at all wastewater treatment facilities in the U.S. On a state-by-state basis, generation rates range from 720,000 MT/day (dry) in California to as little as 2800 MT/day (dry) in Wyoming (Bastian, 1997). Perhaps of greater importance is the range of sewage sludge generation rate at individual wastewater treatment facilities. A plant serving a city of 1 million residents will generate about 100 tons/day (dry) of sewage sludge (Bastian, 1997). Table III-1 summarizes city population in the U.S. These results show that a plant size of 27 MT/day (dry) would be appropriate for a large number of cities. This size is also a credible scale-up of the 5 MT/day pilot plant to be tested during Phase IV.

Table III-1. City Population in the United States

Population	Number of Cities	Sewage Sludge Produced [MT/day(dry)]
100,000 - 300,000	156	9 - 27
300,000 - 600,000	33	27 - 55
600,000 - 900,000	6	55 - 80
900,000 - 1,200,000	6	80 - 110
>1,200,000	8 ^a	>110

Notes:

a - Counts the boroughs of New York individually.

Step 2 - Define Capital and Operating Costs of Integrated System. Based on the 27 MT/day size defined in Step 1, capital and operating costs were generated. M&EBs for the target plant size were prepared to permit sizing of system components and to define operating personnel and utility requirements. Capital costs were obtained by scaling costs for SCWO or other high pressure, high temperature systems and by estimating average labor and utility rates.

Step 3 - Compare Integrated System Costs to Alternate Systems for Hydrogen Generation and Use. Once capital and operating costs were obtained, SCWG hydrogen production costs were compared to those resulting from other sources of production, including natural gas reforming and alternate methods of biomass gasification (Mann, 1995). The negative cost of sewage sludge disposal was an important driver in the cost analysis showing that SCWG of sewage sludge was competitive with other methods of hydrogen production.

Step 4 - Discuss SCWG Integrated System with Regional Wastewater Treatment Facilities. The proposed plant design was then discussed with Encina personnel to obtain their perspective and how they and other wastewater treatment facilities might respond to the analysis. While Encina has an existing treatment system for sewage sludge, disposal of residue is a significant cost, most of which they could avoid with SCWG. Also of interest to them is the potential to avoid the use some of the of treatment equipment associated with sludge treatment. The current treatment systems incorporate large tanks, numerous pumps and valves, extensive piping, are labor intensive and are sensitive to operating conditions. Avoiding these treatment steps was deemed to be a more likely long-term driver for incorporation of SCWG for sewage sludge treatment than disposal costs of treated secondary sludge, particularly if they simply handed off the sludge to a commercial operator of the SCWG system.

Step 5 - Define Demonstration Program and Related Funding Requirements for Phases II thru IV of the Program. Having determined that SCWG hydrogen production was cost

effective and that a potential market may exist for systems at a large number of wastewater treatment facilities, the technology development, technology validation, and scale-up demonstration in Phases II through IV of the DOE program were defined and associated funding requirements defined (see Ch. IV).

Step 6 - Prepare Financial and Long-Range Marketing Plans. Phases II through IV will be followed by a near-commercialization demonstration test program with the SCWG system at a regional wastewater treatment facility. This will include a year or more of on-site operation to provide first-hand operating experience by facility personnel. This will lead into the design of the 27 MT/day SCWG system and its commercial sale to wastewater treatment authorities. The financial requirements for the near-commercial and commercial systems were developed based on this scenario for inclusion in the business plan.

Step 7 - Prepare the Business Plan. Input from Steps 1 through 6 above were integrated into the business plan encompassing SCWG development through near-commercial demonstration testing and into the start of commercial activities. BizPlan Templates were used as guides for producing text, while financial projections were summarized in budgetary tables.

III.B RESULTS AND EVALUATION

The following sections present the business plan and an evaluation of the findings.

III.B.1 Business Plan

The business plan presented below includes (1) a vision/mission statement, (2) company overview, (3) product strategy, (4) market analysis, (5) marketing plan, and (6) financial plan. This format is based on the recommended approach in Biz Plan Builder, and serves to define the essential requirements for developing a new business.

Vision/Mission

Present Situation

The beneficial use of biomass for the production of hydrogen promises to be a key element in developing a hydrogen-based economy that can lead to energy independence for the U.S. and long-term reduction in the growth of atmospheric greenhouse gases. SCWG has been found to be competitive with and potentially superior to more traditional means of producing hydrogen from biomass, particularly for niche feedstocks with high moisture or hazardous waste contents. Supercritical water gasification (SCWG) of biomass has the

potential to produce hydrogen as a revenue-producing product from feeds with high moisture or hazardous waste contents, not suitable for gasification by other means, that might otherwise be considered waste streams, e.g., sewage sludge and municipal solid waste. This will result in hydrogen production costs that are significantly lower than those associated with biomass feeds derived from a dedicated feedstock supply system. While alternative sewage sludge disposal methods exist or are being developed, virtually all involve cost penalties to wastewater treatment facility operators. Thus sewage sludge can be viewed as one of the primary biomass feeds for SCWG systems designed for cost-effective hydrogen production and power generation, and hence a near-term market. Eventually, the market can be expanded to include other centralized biowastes such as pulp-mill wastes or less centralized agricultural wastes. Ultimately, the enormous market of municipal solid waste can be developed by combining it with wastes with high moisture content, and by reducing transportation costs to ever-more-distant landfills.

There are, however, several factors that may limit the near-term applicability of SCWG for hydrogen production. At the present time, a hydrogen-based economy does not exist and it is likely to be several decades before one develops that could make use of SCWG-produced hydrogen on a large, widely-dispersed scale. While near-term "across-the-fence" sales of hydrogen are possible, these are likely to occur only in areas that make significant use of hydrogen, e.g., those near oil refineries or other large users. Thus near-term economic justification for SCWG system sales might be driven mainly by avoided sewage sludge disposal costs or similar local circumstances instead of revenue from hydrogen generation. However, it does appear that cost avoidance for sludge disposal may be a sufficient economic incentive for development of SCWG.

A second factor is the relative immaturity of the SCWG technology vis-à-vis that which is normally accepted as viable and market-ready for large-scale, commercial installations such as municipal wastewater treatment facilities. While both laboratory- and pilot-scale SCWG tests have shown favorable generation of hydrogen from biomass, the data base is limited at this time. Gasification efficiencies and hydrogen yields are still somewhat uncertain, and the affects of many process variables are not fully characterized. However, the tests to date form a strong basis for additional developmental testing to demonstrate key features related to SCWG process and equipment design; plant scale-up; and reliability, availability, and maintainability verification.

The following sections of the business plan present the framework for development of SCWG as a commercial business based on the following provisos:

1. A hydrogen economy continues to develop that is increasingly focused on hydrogen production from biomass feeds versus feedstocks that contribute to increased CO₂ loading in the atmosphere (e.g., methane reforming).
2. Development, validation and scale-up testing in Phases II through IV of the GA)/ DOE SCWG program are successful in verifying performance and cost projections.
3. Technology transfer from parallel developments in SCWO continues, minimizing the need for SCWG-unique development.

Many of the features included in a typical near-term business plan, e.g., definition of business type, management team members, details of manufacturing and supply, have not been described in detail since they are dependent on the outcome of pre-commercial activities planned for the next several years. However, it is envisioned that the business will develop as a natural extension of GA's on-going supercritical water oxidation (SCWO) program that is several years ahead of SCWG development and commercialization. For the sake of clarity, the name SCWG Systems will represent the business entity in the remainder of the business plan.

Vision/Mission Statement

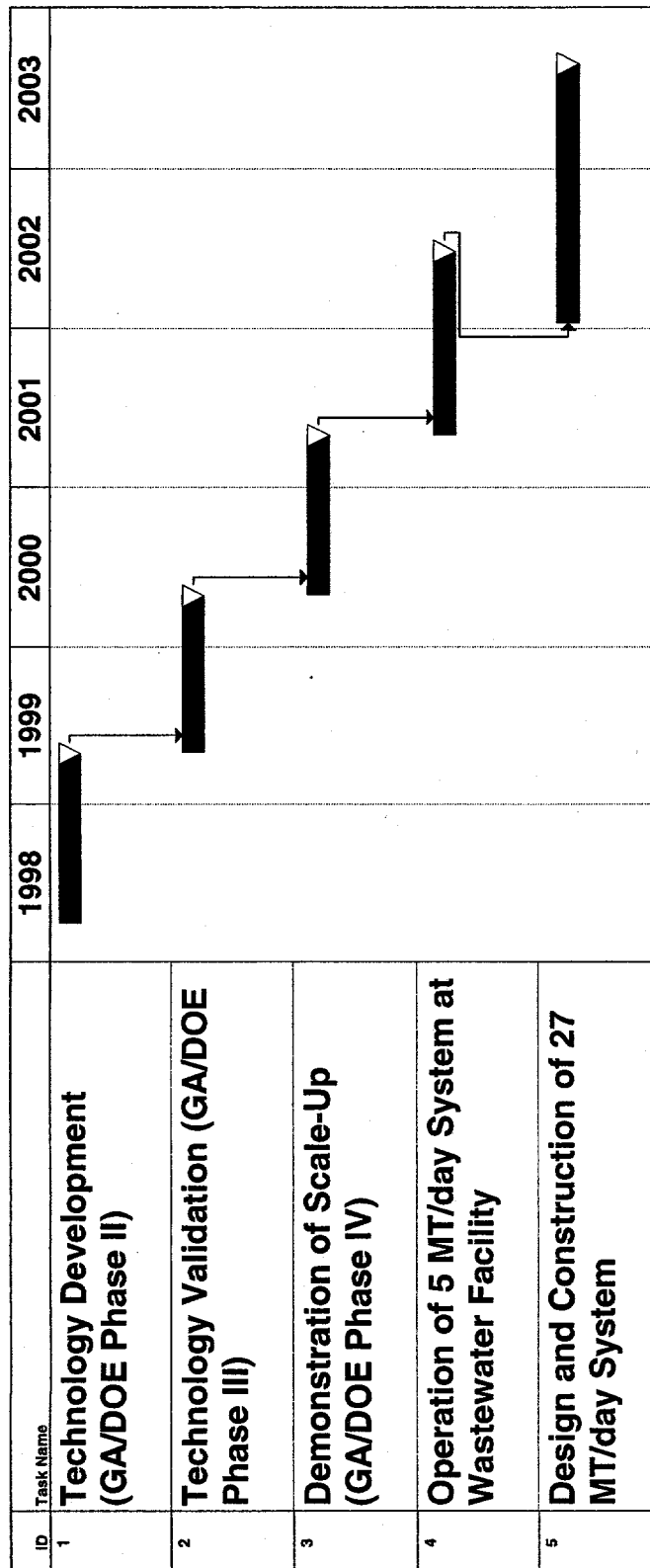
Our vision is that SCWG Systems will become a dominant source for environmentally friendly, sustainable production of hydrogen in the 21st century, particularly from municipal or industrially derived wastes with zero or negative value. To realize this vision, our mission is to become the provider of reliable, cost-effective SCWG systems and services for the production of hydrogen and power from niche biowastes with high moisture or hazardous waste contents. Our near-term focus for the business will be to provide systems and services to the wastewater treatment industry for the disposal of sewage sludge and concomitant production of hydrogen. As we develop the technology and market for SCWG, we will expand our target market to other large, reliable sources of negative-value biomass generators such as pulp and paper mills, food processors and municipal solid waste collectors.

Goals and Objectives

The primary goals and objectives for development of SCWG as a successful business for hydrogen production are described below. Our plan is focused on sewage sludge as the near-term entry market. Fig. III-1 presents a summary timetable of pre-commercial, near-commercial and commercial activities.

1. Incorporate lessons learned during pre-commercial SCWG technology development and demonstration effort. Under Phases II through IV of the GA/DOE program preceding commercial activities, pilot-scale testing with sewage sludge feed will be completed in a one-fifth commercial-scale system to demonstrate key aspects of the SCWG process. The results of this 3-year test program will be reflected in changes and upgrades to the skid-mounted pilot system hardware and operations. This effort, and the testing that goes before it, will build on the 15 years of SCWO experience that GA has acquired during the construction and operation of over half a dozen SCWO pilot plants.
2. Demonstrate reliable, cost-effective operation of the SCWG pilot system at a wastewater facility. The upgraded pilot system will be moved to a wastewater treatment facility for on-site testing to demonstrate long-term operation, and to develop industry interest and confidence in SCWG for sewage sludge treatment and hydrogen production. Design of a commercial-size SCWG system will also be started during the latter part of this work, incorporating lessons learned from on-site testing and operations. The initial commercial plant size, 27 MT/day, is compatible with the processing rate of a large number of wastewater treatment facilities and represents a credible five-fold scale-up in throughput over the pilot-scale system. Simultaneously, active marketing of SCWG systems will take place with the wastewater industry, with the intent of acquiring the initial customer for the system.
3. Sell the initial SCWG system on an equipment or "take-or-pay" basis. Based on successful completion of on-site pilot testing at a wastewater facility, the first SCWG integrated systems will be sold to a wastewater treatment facility, possibly with a lease-back provision to an independent operating company. Following successful operation of this unit, additional sales of this size unit are anticipated during out years.

FIG. III-1
SCHEDULE FOR SCWG DEVELOPMENT AND COMMERCIALIZATION



Company Overview

Legal Business Description

SCWG development during Phases II through IV of the GA/DOE program and the near-commercial operation at a wastewater treatment facility will be carried out as an activity of Advanced Process Systems Division at GA. Subsequently, the optimum business form for the commercial SCWG Systems activities has not been defined at this time. It is anticipated that this would be resolved near the end of Phase 4 of the GA/DOE program, prior to the start of the marketing effort. However, some form of partnership is likely to be appropriate in order to finance and provide all other elements necessary for a successful business.

Management Team

No specific management team has been identified for commercial activities at this time. During Phases 2 through 4, it is currently envisioned that the existing members of the GA project team will oversee development, validation and demonstration activities. After it has been verified that SCWG is a cost-effective, reliable source of hydrogen and that a market exists for the technology, a management team experienced in commercial startups will be put in place.

Board of Directors

The nature and composition of the Board of Directors for the commercial SCWG Systems business would depend in part on evolution of the technology and market. However, it can be envisioned that the Board would comprise representatives for GA and the wastewater industry.

Product Strategy

Research and Development

The pre-commercial research and development program is embodied in Phases II through IV of the GA/DOE SCWG technical plan. Progressive steps are defined that build on work to date in Phase I of the GA/DOE program. Additional work to enhance system performance will be a natural outgrowth of near-commercial testing at the wastewater facility. GA brings extensive experience with incorporating process and product improvements into commercial systems based on operating experience.

System Fabrication

GA has broad experience with the design, fabrication and integration of components and equipment for both small- and large-scale systems. This has been amply demonstrated during GA's SCWO program, where a number of pilot plants of increasing size have been designed, fabricated, and tested. GA has also built power plants, large-scale hazardous waste disposal facilities, as well as a wide variety of industrial systems for the U. S. and foreign Governments and commercial clients. GA will use this experience to oversee fabrication of SCWG-specific components (e.g., liquefier/high pressure pump, gasifier vessel), procure off-the-shelf hardware and equipment, assemble system components, and perform checkout prior to delivery to the customer.

Market Analysis

Market Definition

The near-term market for SCWG technology is the processing of biomass streams for which substantial disposal costs are currently involved – specifically sewage sludge. Longer term, leading candidate wastes include pulp and paper mill sludges; food processing wastes such as bagasse, wheat straw, potato peelings, corn starch, and fruit processing residues; and municipal solid waste operations for which collection and transportation cost are becoming prohibitive. These wastes are characterized as having high moisture content and/or toxic or corrosive chemicals that are difficult to handle by more traditional gasification methods.

A municipal treatment plant serving a city of 1 million residents will generate about 100 tons/day of sewage sludge (Bastian, 1997). A city of 300,000 residents can thus support a plant of the size proposed for initial commercial installations. To define the prevalence of this size community, Table III-2 summarizes city populations in the U.S. taken from the 1990 census. Many of the cities listed will have multiple treatment facilities, and the metropolitan/suburban areas surrounding these cities may well double the number of candidate sites. Thus, there are estimated to be several hundred municipal plant sites in the U.S. where a 27 MT/day or larger SCWG system could be installed. It should also be noted that the size of the sewage sludge market is increasing as more stringent disposal regulations have come into effect over the past 25 years.

Table III-2. City Population in the United States

Population	Number of Cities
100,000 - 300,000	156
300,000 - 600,000	33
600,000 - 900,000	6
900,000 - 1,200,000	6
>1,200,000	8 ^a

Notes:

a - Counts the boroughs of New York individually.

Other biomass waste streams exist today that are amenable for gasification and hydrogen production. There are approximately 160 pulp mills operating in the U.S., ranging in size from less than 5 MT/day to about 150 MT/day, with a median sludge generation rate of about 20 MT/day (Blosser and Miner, 1986). Data on agricultural and industrial sludges have not been obtained for this plan, but could possibly add several hundred candidate sites. Municipal solid waste generation rates are huge compared to sewage sludge wastes, and serve as a future growth market requiring additional pretreatment steps and refinements for handling toxic and corrosive constituents. But these factors are again ideally suited for the SCW environment. In the industrialized countries worldwide, sales opportunities from just sewage sludge, pulp, and agricultural wastes number in the thousands. SCWG ultimately offers a means of closing the loop on mankind's generated biomass wastes, while deriving additional energy and environmental benefits.

Customer Profile

Wastewater treatment facilities are the likely initial customers for SCWG systems. With few exceptions, they have established equipment and practices for the primary and secondary treatment of sewage sludge. However, because of the operating costs associated with the existing treatment system equipment and disposal costs for residual sludge solids, it is expected that SCWG production of hydrogen can be an integrated unit operation at existing plants or at plants that will be built or upgraded in the future. The wastewater facility will have to be amenable to becoming a hydrogen supplier or electricity provider, either directly with an owner-operated unit or indirectly through a take-or-pay agreement with a system likely operated on their site. Thus, finding appropriate locations for the initial systems is a key factor.

Competition

In the United States, 54% of the municipal sludge production is disposed of by land application to cropland, forests, reclamation sites, lawns, park land, etc. Approximately 18% is disposed of in landfills and 19% is incinerated (Bastian, 1997). Assuming the disposal cost paid by Encina Wastewater Authority, located in Carlsbad, CA, is typical for land application, our calculations show that SCWG should be economically attractive for a substantial fraction of municipal treatment plants. While both land application and SCWG are viewed as environmentally friendly, land application represents a cost penalty whereas SCWG will be a revenue producer (even in the absence of a disposal credit).

A brief search of the patent literature indicates a number of proposed uses of sewage sludge other than as a soil conditioner, such as a raw material for the manufacture of fuels or chemicals (the same general idea as anaerobic digestion), an additive in the smelting of ferrous materials, use as a fire suppressant, fuel for cement manufacture, an additive to road asphalt, and a bioremediation agent. But none of these looms large in the current planning of wastewater treatment facility operators.

Conceivably, gasification methods other than SCWG may be compatible with the processing of sewage sludge. But the high moisture content and heavy metals content exacerbate problems of sewage sludge processing by other gasification methods.

It is difficult to assess how these competing technologies will affect the market share accessible to SCWG. However, a number of the proposed technologies would appear to have limited capacity and/or be favorable only in fairly specific locations.

Risk

The financial basis of implementing SCWG technology is not ideal because it requires a large up front investment that will require a number of years to achieve a favorable return on investment. This extended time frame for payback on a first-of-a-kind technology may cause reluctance on the part of the potential initial users, even though similar payback periods are common for large, capital-intensive systems. This factor will undoubtedly play a role in the commercialization and growth of SCWG technology.

Significant political barriers to the implementation of SCWG are not anticipated. In fact, implementation of the technology is expected to be promoted and even partially subsidized by local, state and federal government organizations, particularly if global concerns over greenhouse gases continue to grow.

Following successful demonstration testing, SCWG Systems will begin promotion and sales of full-scale commercial units. The primary hurdle to overcome at this stage is likely to be the plant capital cost and its recovery. It seems unlikely that the first plant, or even the first several plants, could be sold outright. Financial backing will be required from the technology provider, perhaps in combination with the end user or an industrial, financial, and/or governmental partner. A consortium of interested Government and commercial entities might be the ultimate vehicle for financing the first few plants, much like other utility providers. Thus, the focus for the company will be to bring in other interested parties. In order to attract industrial or private venture capital, a significant patent position, either with in-house or exclusively licensed technology, is likely to be required.

Marketing Plan

Sales Strategy

Despite the well-established practices and benign or beneficial uses, sewage sludge nonetheless represent a cost liability to wastewater treatment facility operators. This point has been made repeatedly by our contacts at the Encina facility. The focus of the marketing effort will be to highlight the production of hydrogen and energy from sewage sludge using SCWG technology, allowing facility operators to reduce operating expenses near-term by avoiding sewage sludge disposal costs, and lessening or eliminating long-term operating expenses related to secondary treatment of sludge. Successful operation of the 5 MT/day pilot plant at a regional wastewater facility will provide an SCWG operational data base. This will build confidence in the reliability and economic performance of systems and provide the necessary customer input for design of the commercial-scale system.

Advertising and Promotion

The near-commercial operation of the 5 MT/day system at a regional wastewater facility will serve as the single most important means of promoting (through demonstration) the SCWG technology. Other wastewater facility operators will be invited to observe first-hand the on-site operations. Video tapes of the operations will be made available, together with a worldwide web site and interactive analysis with potential clients. The marketing effort will be aided by the publication of technical articles in trade journals, and presentations at trade and professional conferences.

Financial Plan

Assumptions

Section IV presents a detailed description of planned activities during Phases II through IV of the GA/DOE SCWG development program and the follow-on near-commercial SCWG demonstration at a local wastewater treatment facility. Specific tasks have been defined and corresponding budgets prepared, as discussed below.

Financial assumptions for subsequent commercial activities were also developed. The following are the primary assumptions used to develop capital, installed and operating costs for commercial-scale systems. Design and costing of the high pressure components, in particular the gasifier technology, relied heavily on GA's prior experience in the SCWO field.

1. System throughput is 27 MT/day (dry) of combustible sewage sludge
2. Feed material concentrations of 20% and 40% were evaluated. Ash content in the feed after concentration was 1%.
3. A scaling exponent of 0.6 was applied to GA SCWO equipment to calculate component costs at the appropriate throughputs.
4. All equipment was specified to provide at least 20% excess capacity.
5. Prices for the feed pretreatment process, sewage sludge storage tank, sewage sludge transfer pump, emulsifier/macerator, progressive cavity pump, sludge concentrator and sludge liquefier were determined from equipment vendor quotes and engineering judgment.
6. A bulk items factor of 1.35 times major capital equipment was used.
7. A factor of 0.6 times major equipment costs was used to calculate design and fabrication costs for a first-of-a-kind system. A factor of 0.15 times the major equipment costs was used to estimate fabrication costs for subsequent 27 MT/day systems.
8. Facilities upgrade costs were assumed to be 0.1 times the major equipment cost.
9. Startup costs were assumed to be 0.2 times the major equipment cost.
10. The plant is staffed by three operators and one supervisor during round-the-clock operation
11. The plant operates 330 day/year

Financial Summary

Tables III-3 through III-6 present the budgets for Phases II through IV of the GA/DOE SCWG development program as well as the follow-on near-commercial pilot plant demonstration at a local wastewater treatment facility. Total costs for the GA/DOE activities only are summarized in Table III-7 and in Sec. V.D.

Table III-8 summarizes the capital and operating costs developed for the 27 MT/day SCWG system for varying operating scenarios. Appendix C presents the backup data in spreadsheet form used to obtain these values. The spreadsheets were developed expressly for SCWG evaluation and incorporate the assumptions presented above.

III.C EVALUATION

The financial plan presented for Phases II through IV and near-commercial activities reflects GA's belief that commercial deployment of SCWG systems can occur within five years. The plan incorporates cost-shared funding by both GA and DOE through Phases II, III, and IV, with GA, and perhaps a wastewater treatment facility operator, assuming responsibility for near-commercial operation.

As noted in Sec. II.A.2, comparison of the cases for feeds with 20 and 40 wt% sewage sludge indicates a significant capital cost advantage for processing more highly concentrated solids. This results from the requirement to process only about half the total volume of feed material (sewage sludge and water) with the 40 wt% feed. However, because the plants process the same quantity of sewage sludge, the hydrogen production from the two plants is the same. Total installed capital cost for the nth plant is \$6.1 million for the 40% case and \$9.3 million for the 20% case. The total installed capital cost for a first-of-a-kind plant is \$7.1 million for the 40% case vs. \$10.8 million for the 20% case. Based on these data, together with the assessment of sludge concentration methods, 20 wt% feed was dropped from further consideration in the belief that an effective feed concentration system can be developed for a 40 wt% feed stream.

**TABLE III-3
GA/DOE PROGRAM
PHASE II TECHNOLOGY DEVELOPMENT BUDGET**

	Task 100	Task 200	Task 300	Task 400	Task 500	Hrs	Cost
LABOR							
Project Manger					480	480	
Senior Staff Engineer	480	960	960	480		2,880	
Senior Engineer	480	640	960	480		2,560	
Non-exempt staff support	640	960				1,600	
LABOR HRS SUBTOTAL	1600	2560	1920	960	480	7,520	
LABOR COST SUBTOTAL	\$153,187	\$258,950	\$204,675	\$102,338	\$68,600		\$787,750
OTHER							
Analysis	\$20,000	\$25,000					\$45,000
Materials	\$175,000	\$200,000					\$375,000
Facilities	\$30,000	\$25,000					\$55,000
Consultant			\$25,000				\$25,000
OTHER SUBTOTAL	\$225,000	\$250,000	\$25,000	\$0	\$0		\$500,000
TOTAL	\$378,187	\$508,950	\$229,675	\$102,338	\$68,600	7,520	\$1,287,750

**TABLE III-4
GA/DOE PROGRAM
PHASE III TECHNOLOGY VALIDATION BUDGET**

	Task 100	Task 200	Task 300	Task 400	Hrs	Cost
LABOR						
Project Manger				1440	1,440	
Senior Staff Engineer	160	2560	960		3,680	
Senior Engineer	320	1960	960		3,240	
Non-exempt staff support		960			960	
LABOR HRS SUBTOTAL	480	5480	1920	1440	9,320	
LABOR COST SUBTOTAL	\$47,856	\$572,460	\$959,216	\$204,703		\$1,784,235
OTHER						
Analysis			\$20,000			\$20,000
Materials			\$1,500,000			\$1,500,000
Facilities			\$50,000			\$50,000
Consultant	\$10,000					\$10,000
OTHER SUBTOTAL	\$10,000	\$0	\$1,570,000	\$0		\$1,580,000
TOTAL	\$57,856	\$572,460	\$2,529,216	\$204,703	9,320	\$3,364,235

**TABLE III-5
GA/DOE PROGRAM
PHASE IV DEMONSTRATION OF SCALE-UP BUDGET**

	Task 100	Task 200	Task 300	Task 400	Hrs	Cost
LABOR						
Project Manger				480	480	
Senior Staff Engineer	480	480	960		1,920	
Senior Engineer	480	480	960		1,920	
Non-exempt staff support	480	480	960		1,920	
LABOR HRS SUBTOTAL	1440	1440	2880	480	6,240	
LABOR COST SUBTOTAL	\$143,866	\$143,866	\$287,732	\$68,234		\$643,698
OTHER						
Analysis		\$50,000	\$50,000			\$100,000
Materials/leases		\$150,000	\$50,000			\$200,000
Facilities		\$25,000	\$25,000			\$50,000
Consultant						\$0
OTHER SUBTOTAL	\$0	\$225,000	\$125,000	\$0		\$350,000
TOTAL	\$143,866	\$368,866	\$412,732	\$68,234	6,240	\$993,698

**TABLE III-6
NEAR-COMMERICAL DEMONSTRATION AT
WASTEWATER TREATMENT FACILITY**

	Task 100	Task 200	Hrs	Cost
<u>LABOR</u>				
Project Manger		320	320	
Senior Staff Engineer	1920	960	2,880	
Senior Engineer	1920		1,920	
Non-exempt staff support	480		480	
LABOR HRS SUBTOTAL	4320	1280	5,600	
LABOR COST SUBTOTAL	\$443,592	\$162,645		\$606,237
<u>OTHER</u>				
Analysis				\$0
Materials/leases	\$750,000			\$750,000
Facilities				\$0
Consultant				\$0
OTHER SUBTOTAL	\$750,000			\$750,000
TOTAL	\$1,193,592	\$162,645	5,600	\$1,356,237

Table III-7. Budgetary Estimate for Phases II through IV

Phase	Budget (\$)
Phase II, Technology Development	1,287,750
Phase III, Technology Validation	3,364,235
Phase IV, Demonstration of Scale-Up	993,697
Total for all phases	5,645,682

Table III-8. Summary of SCWG Capital and Operating Costs

Parameter	20 wt% Sewage Sludge Feed	40 wt% Sewage Sludge Feed	40 wt% Sewage Sludge Feed with Lower H ₂ Yields
Capital Cost, Initial Plant, \$	10,834,000	7,094,000	7,068,000
Capital Cost, Nth Plant, \$	9,345,000	6,123,00	6,100,000
Operating Cost Without Feed Credit, \$	(737,000)	(774,000)	(487,000)
Operating Cost With Feed Credit, \$	(1,628,000)	(1,665,000)	(1,378,000)
Break-Even Point with Feed Credit, yr	6.5	4.5	5.5
Internal Rate of Return @ 10 yr, %	8%	20%	14%

Operating costs for the 40% case incorporates an average hydrogen credit of \$10/GJ obtained from a report by Mann (1995). A disposal cost credit of \$90/MT(dry) has been taken based on discussions held with the Encina Wastewater Authority and takes account of a \$30/MT ash disposal cost. Over and above the credit for sludge disposal costs, no credit is taken for avoided sewage sludge processing costs (additional handling plus anaerobic digestion). Another potential credit which has not yet been evaluated is for recovery of carbon dioxide from the flue gas. The financial break-even point occurs between 4.5 and 5.5 years, depending on hydrogen yield. After 10 years, an internal rate of return of 14% to 20% is achieved, again depending on hydrogen yield.

The cost of the SCWG process has been compared to the Battelle biomass gasifier. A demonstration of the Battelle technology is currently starting up in Burlington, Vermont (Chemical Engineering, p. 23, October, 1997). The plant will gasify 200 ton/day of forest residues and appears to have a capital cost of about \$20 MM. This is reasonably consistent with the cost estimates of Mann (1995), which arrived at a total installed capital cost of about \$30 MM for a 300 ton/day plant.

The smallest capacity Battelle gasifier plant evaluated by Mann processed 27 MT/day of dry woody biomass, essentially the same size as the SCWG units described here. The SCWG process produces a comparable amount of hydrogen as the BCL gasifier, although the latter process was evaluated with a feedstock of dried woody biomass containing only 11 wt% moisture (following drying) versus sewage sludge with a feed moisture content of 60% (following concentration). Thus, the SCWG system can produce high hydrogen yields from high water content feedstocks that are incompatible with more conventional gasifiers. The SCWG and BCL units also produce similar amounts of byproduct steam; however, the SCWG steam is available at a significantly higher temperature and pressure.

For the optimum scenario evaluated by Mann, the Battelle capital gasifier cost was estimated to be approximately \$5 million. Annual operating costs of the BCL gasifier were estimated to be an operating credit of \$415,000 with woody biomass versus an operating credit of \$1,661,000 for SCWG with sewage sludge. Operating costs highly favor the SCWG scheme due in part to the use of a negative-value feedstock that cannot be readily treated by alternate gasification methods. Similar advantageous operating costs are expected for other niche feedstocks with high moisture or hazardous waste contents. This emphasizes the importance of focusing SCWG marketing where the technology is most advantageous, i.e., on relatively high moisture content, or potentially hazardous waste contaminated negative-value feeds. But even without the credit for sludge disposal, the cost of sludge acquisition is zero compared to the relatively high acquisition cost for woody biomass; thus the SCWG annual operating costs are still a net credit of about \$770,000 compared to a credit of \$415,000 for the BCL gasifier.

We envision that the initial 27 MT/day SCWG system for hydrogen production can be ready for commercial deployment at the end of the pilot plant demonstration phases, estimated to be about five years from the start of Phase II. This assumes that all key technical issues described in Sec. II.B.2 have been resolved and potential concerns of an initial customer are addressed in near-commercial testing of the 5 MT/day pilot plant at a wastewater treatment facility. Design of the 27 MT/day system would commence during the latter part of pilot plant testing and would incorporate lessons learned during on-site operation.

III.D TECHNICAL AND FINANCIAL REQUIREMENTS FOR MANUFACTURING CAPABILITY

The technical requirements foreseen as necessary to achieve commercialization are essentially those described in Section IIB.2 above and summarized in Table II-8. For comparison purposes, over \$75 million has been spent to date by the private and public sectors

on SCWO technology, which is characterized as at the stage of incipient commercialization. A commercial SCWO plant treating 20 L/min of aqueous organic chemicals was commissioned by Huntsman Chemical in 1994, and reportedly has an excellent operational history. It currently appears that the next commercial SCWO plant will be in the Government sector, either for the U.S. Army being installed for treatment of toxic chemicals at Pine Bluff Army Ammunition Plant, and planned as a secondary treatment for waste derived from the destruction of chemical warfare agent, or operated on board a U.S. Navy vessel for the treatment of excess hazardous materials at sea.

Much of the knowledge base developed for SCWO is and will continue to be directly transferable to SCWG, with a concomitant reduction in development costs for SCWG. Nevertheless it is likely that from \$10 to \$20 million will be required to reach the point at which an entity is willing to finance a first commercial plant. Phases II through IV as proposed here, call for over \$5.5 million of GA and DOE funding. This represents an initial success-oriented investment [i.e., it assumes that a) the technology development requirements of Table II-8 are achieved and that b) no major obstacles are encountered and c) that continuing developments in SCWO will be a no-cost benefit to SCWG]. In a less optimistic scenario, developmental hurdles may be encountered, and additional follow-on funding may be required. Additional funding, beyond the initial GA/DOE collaboration, could possibly be provided by a consortium of wastewater treaters and hydrogen users. Potential partners for this stage would likely be gas companies such as BOC, Air Liquide, Praxair or Air Products with hydrogen expertise and an established customer base, and local wastewater treatment plants such as the Encina facility.