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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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GENERAL ATOMICS

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 undergone 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 it's 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.

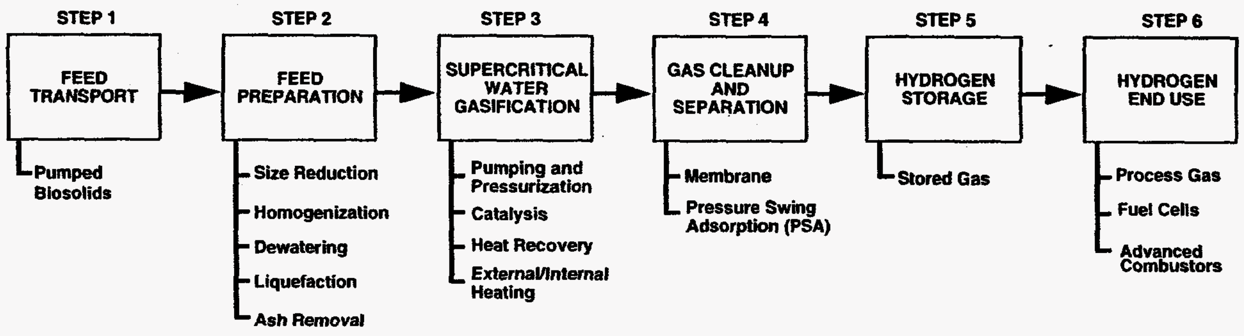
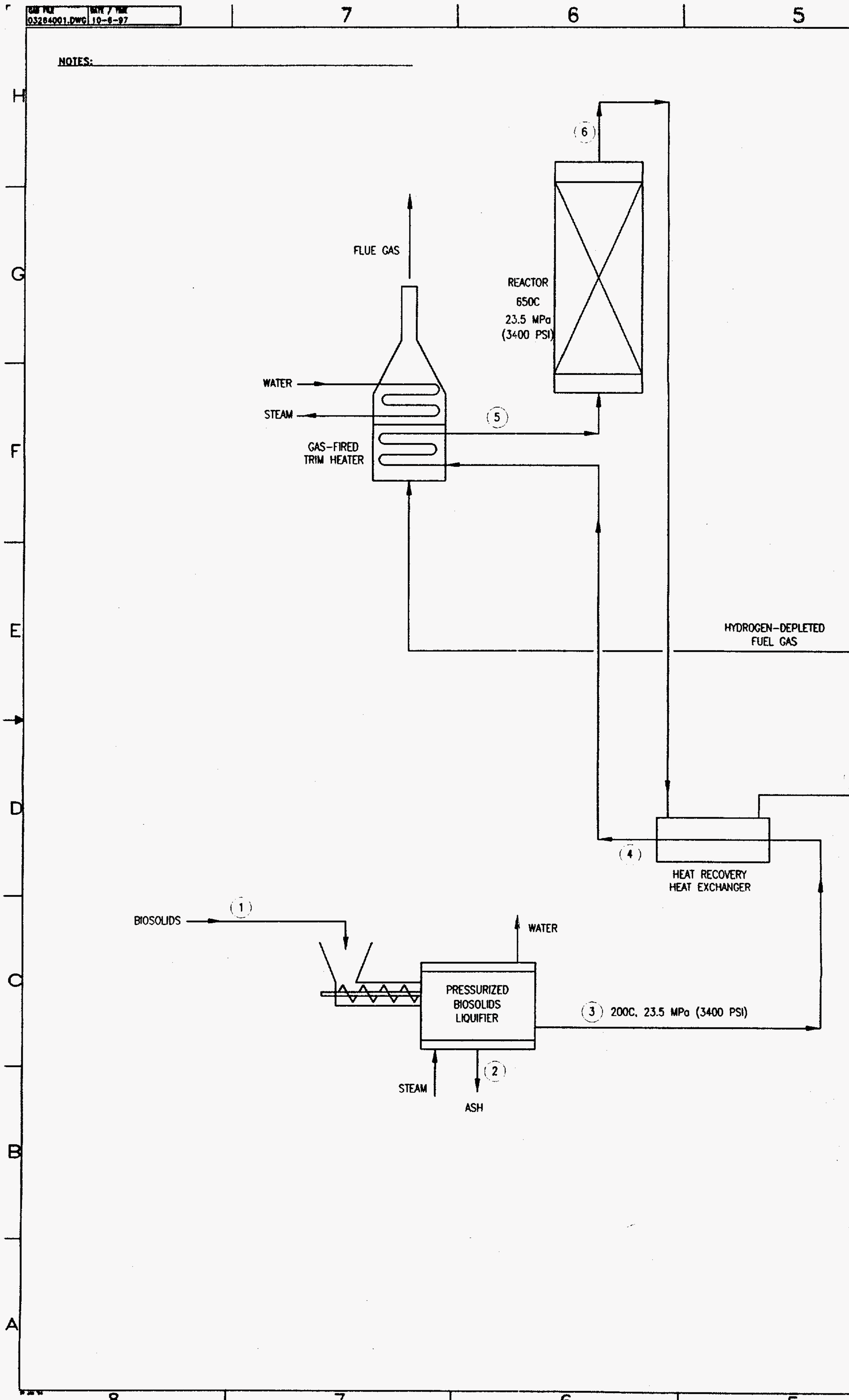


Fig. II-1. Block flow diagram for integrated SCWG hydrogen system

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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REACTOR
650C
23.5 MPa
(3400 PSI)
6
WATER
STEAM
5
GAS-FIRED
TRIM HEATER
HYDROGEN-DEPLETED
FUEL GAS
4
HEAT RECOVERY
HEAT EXCHANGER
BIOSOLIDS
1
WATER
PRESSURIZED
BIOSOLIDS
LIQUIFIER
3
200C, 23.5 MPa (3400 PSI)
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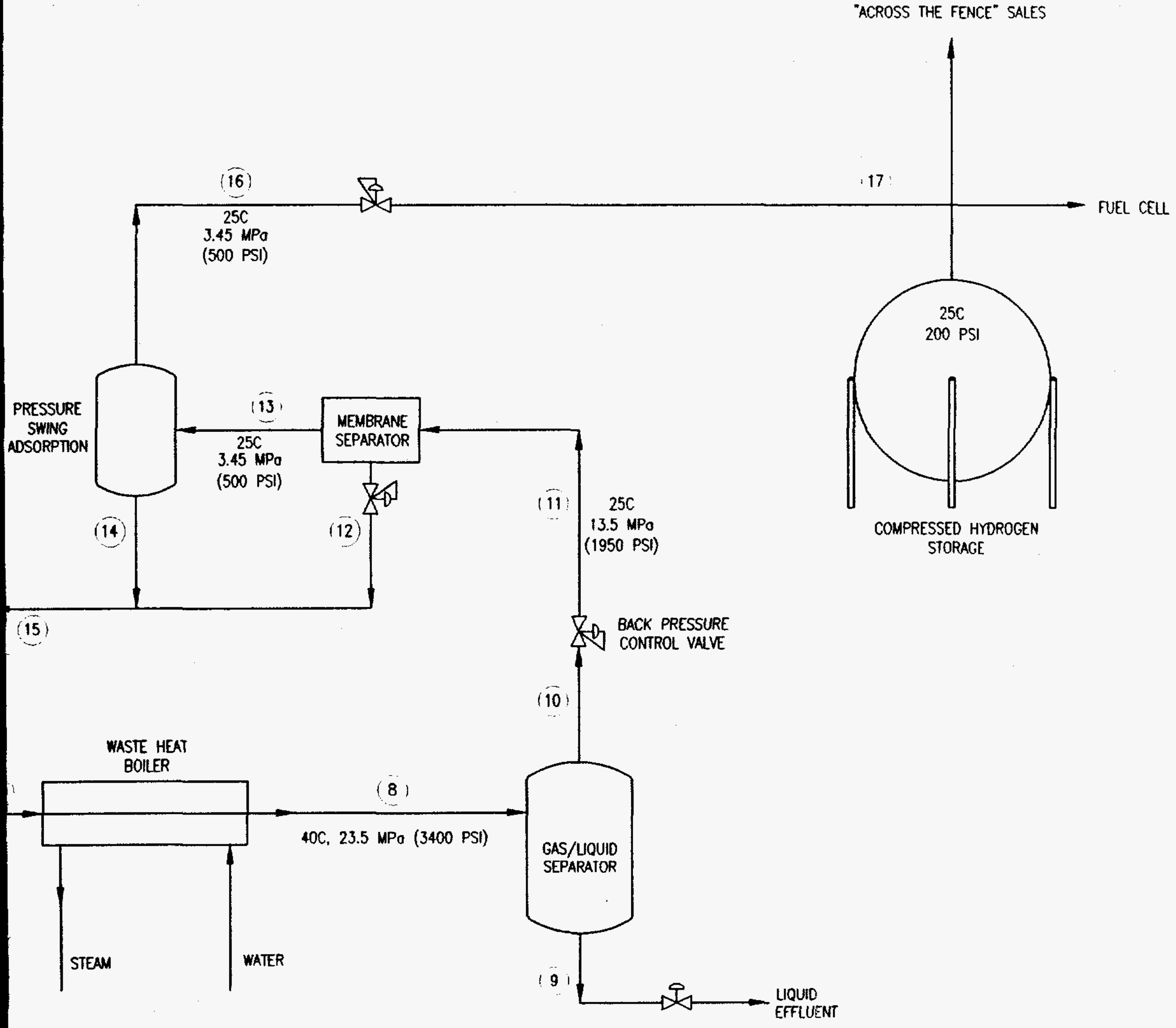

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DIMENSIONS PER ANSI-Y-14.5M
TOLERANCES:
FRACTIONS ± DECIMALS .X ± .XX ± .XXX ± ANGLES ±
ALL MACHINED SURFACES √
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TITLE
BIOSOLIDS GASIFICATION
PROCESS FLOW DIAGRAM

SIZE E
FSCM NO 32334
DWG NO 03264001
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SCALE NONE
SHEET 1 OF 1

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 CO_2, 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 H_2, passes about 40% of the CO_2 and CO, and reduces the CH_4 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 m^3 (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.

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[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_2O, 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	Membrane Fuel Gas	Membrane 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_2O, 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_2O, 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_2O, 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 CO_2 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.

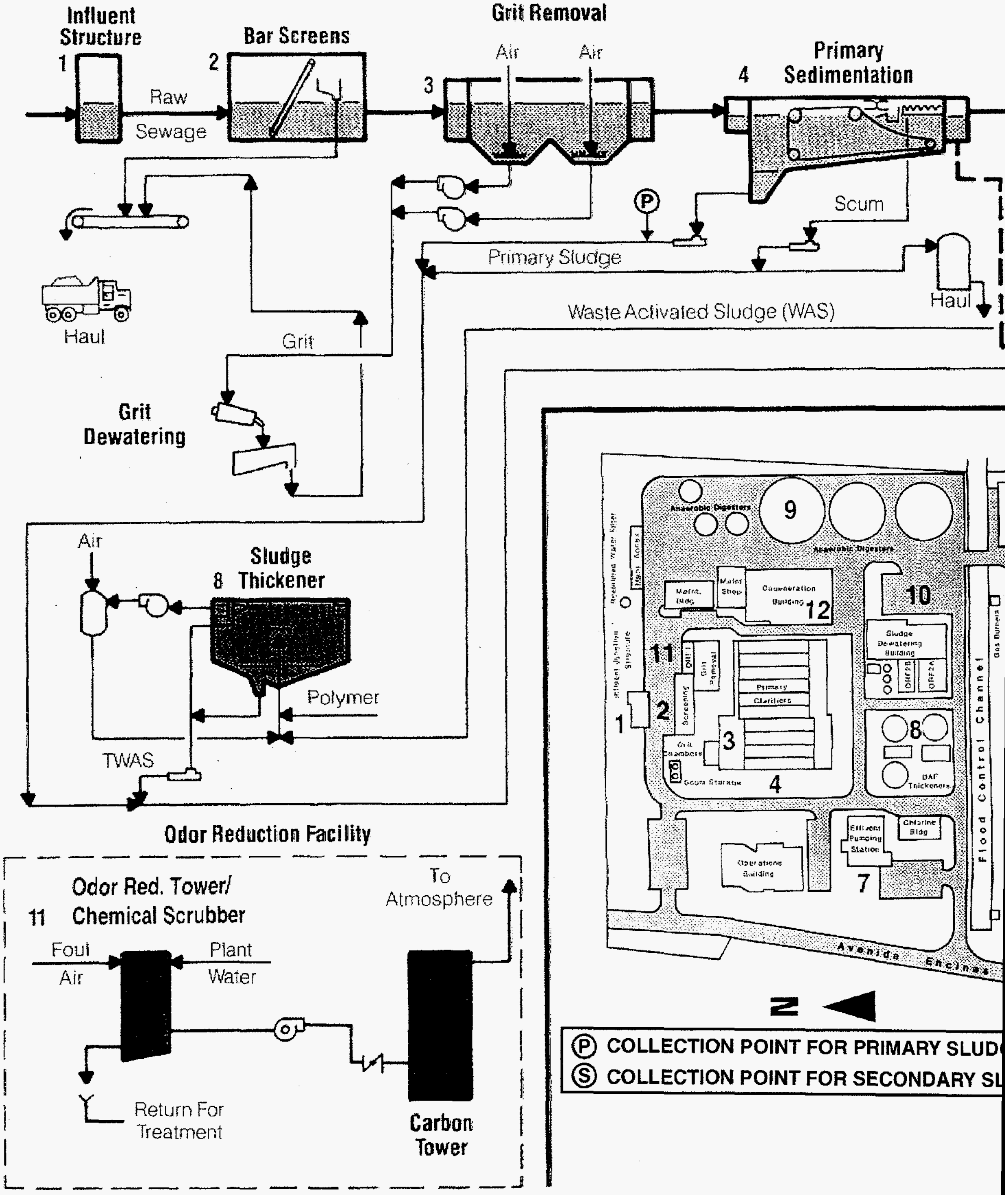
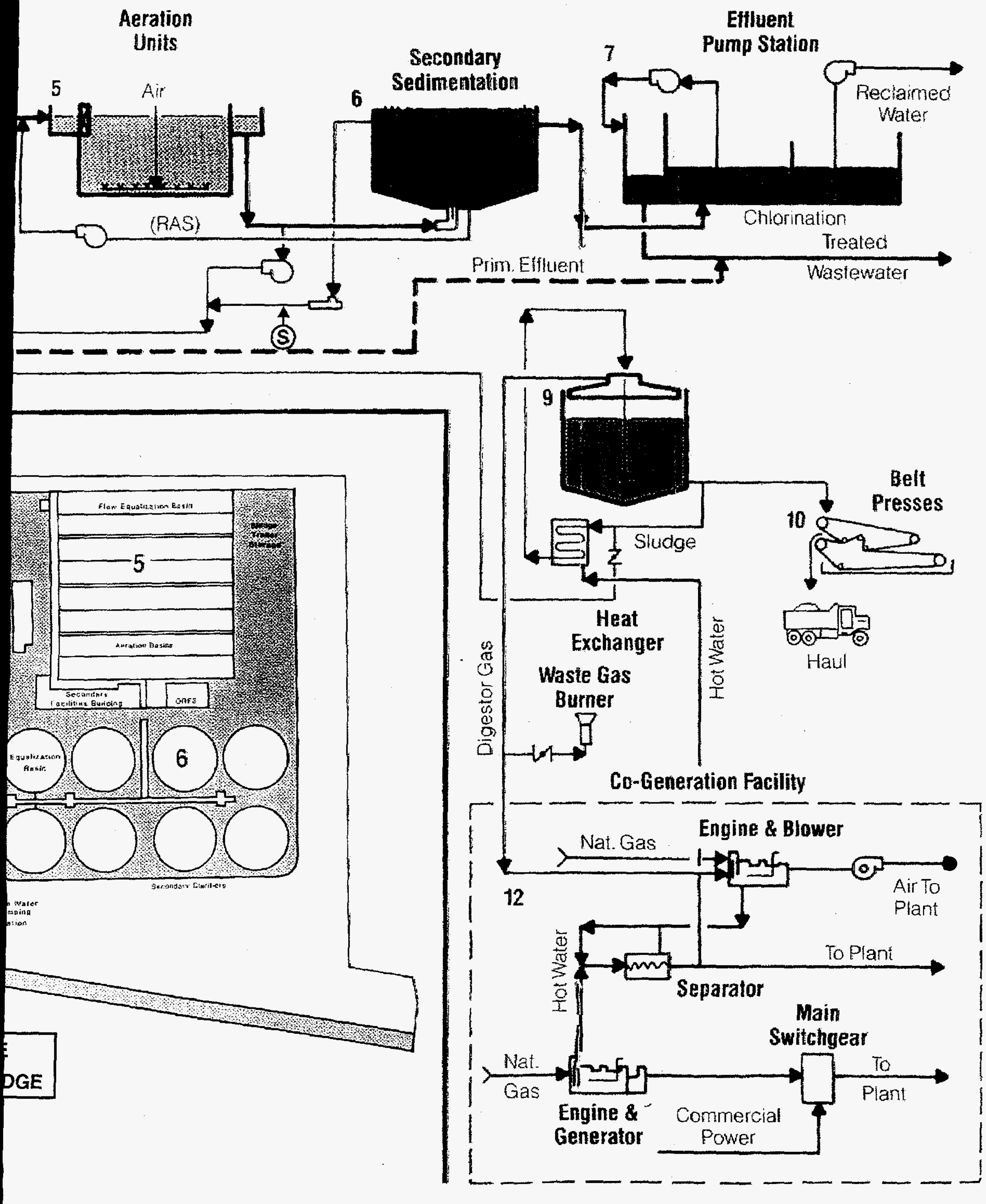


Fig. II-3. ENCINA PROCESS



CHEMATIC AND SITE PLAN

Table II-4. Composition of Combustibles in Biomass Materials

	Primary Sludge[(a)]		Corn Starch[(b)]		Woody Biomass[(c)]	
Element	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 CO_2, CH_4 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 Comparison[2]

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_2O_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

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[2] Antal points our that they have usually observed the following gas composition from sewage sludge blended with cornstarch: 43% H_2, 39% CO_2, 17% CH_4, 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% H_2 to 53% H_2 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

CH_3OH. 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 H_2O, O_2, N_2, CO_2, 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 H_2O, CO, CO_2, and CH_4. 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 m^3 in size. Low pressure spherical vessels are also used, containing about 15,000 m^3 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., H_2O, CO, CO_2, and CH_4) 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 H_2 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.ercc.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 cellulosics 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 to 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 reactor[3]. 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]

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[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 bad 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 H_2 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.

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[5] Note that commercialization of large, centralized SCWG systems does not involve the develpment 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 servers 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 cultralized 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 CO_2 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.

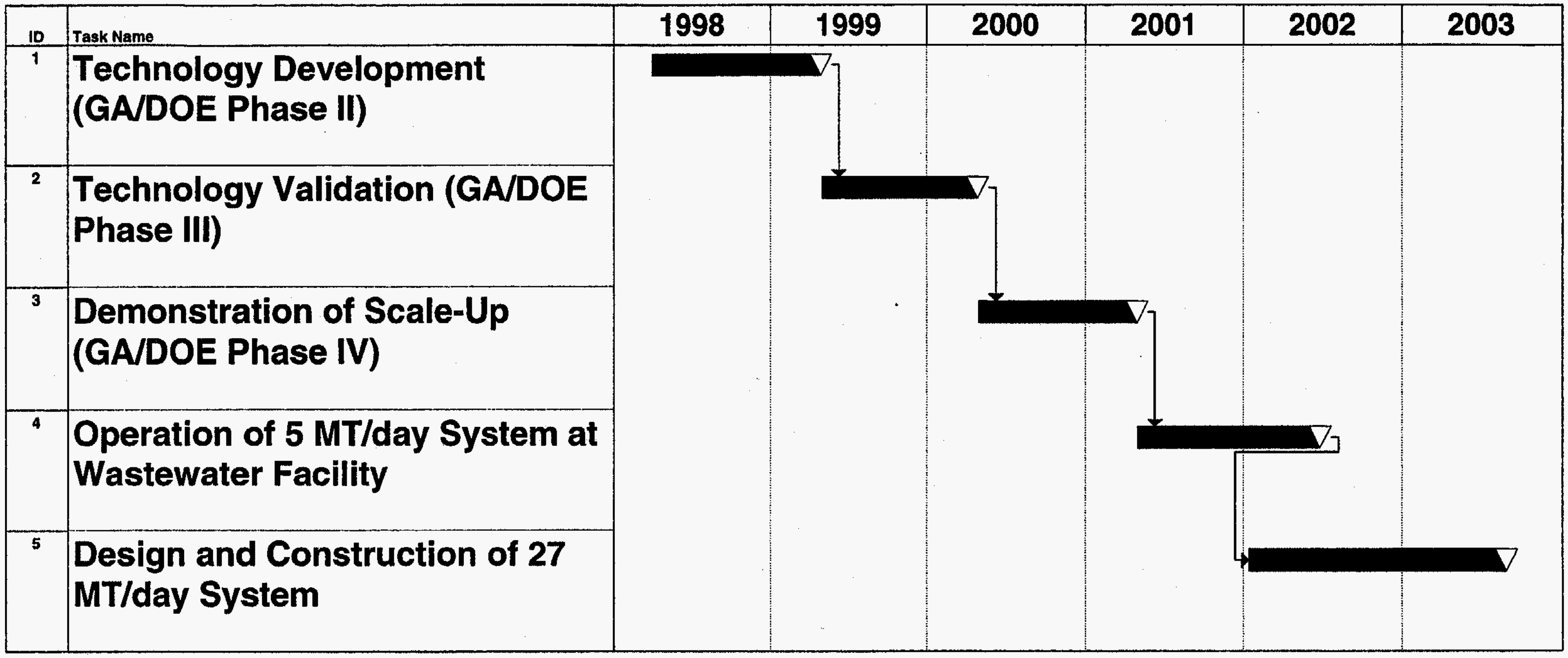
1. Incorporate lessons learned during pre-commercial SCWG technology development and demonstration effort. Under Phases II through IV of the GA/DOE program preceding commercial activities, pilot-scale testing with sewage sludge feed will be completed in a one-fifth commercial-scale system to demonstrate 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 be 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 tern, 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. Bus 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
LABOR				
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**
OTHER				
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**

GENERAL ATOMICS

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 yeild. 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 gasifyer.

We envision that the initial 27 MT/day SCWG system for hydrogen production can be ready for commercial deployment at the end if 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 concorium 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 wastewate treatment plants such as the Encina facility.

IV. PROJECT PLANNING FOR PHASES II - IV

This section describes the proposed workscope and task plans for Phases II through IV of the program. Phase II, Technology Development, comprises additional laboratory- and pilot-scale testing, as well as expanded thermodynamic and kinetics calculations. Phase III, Technology Validation, is focused on design, assembly, and checkout of individual subsystems. Phase IV, Demonstration of Scale-Up, will demonstrate SCWG system operation with the fully integrated 5 MT/day pilot plant to verify generation of hydrogen from biomass during extended tests.

IV.A PHASE II - TECHNOLOGY DEVELOPMENT

IV.A.1 Work Scope and Task Plans

During Phase II, further development of SCWG technology will be performed to resolve knowledge gaps and other critical issues, and to define performance requirements and system interfaces for the Phase III, Technology Validation. The technical issues requiring further development were discussed in Sec. IIB, and summarized in Table II-8.

Task 100 - Feed preparation and Pumping. Demonstrate drying and heating/liquefaction/ash separation/pressurizing/pumping of simulant (corn flakes) and sewage sludge.

1. Design feed liquefaction and pumping system and ash removal system
2. Procure sludge dryer, dried sludge feeder, and pump upgrades
3. Perform pilot-scale tests at GA with the existing, adapted sewage sludge pump
4. Analyze solid feed, liquefied feed, and ash, and document results
5. Key decision point: feasibility of feeding 40 wt% liquefied sewage sludge

Task 200 - Extended Testing. Evaluate alternate catalysts, verify higher H_2 production, and demonstrate extended operation (>8 hr).

1. Perform lab-scale catalyst tests
2. Run short-term pilot-scale tests with alternate catalysts
3. Incorporate liquefied feed system into pilot plant and test
4. Analyze data and document results
5. Decision point: reliable production of 40% to 50% hydrogen (mole fraction)

Task 300 - Process Analyses. Define performance requirements and system interfaces.

1. Perform chemical equilibrium calculations
2. Compare results to lab- and pilot-scale test results
3. Analyze data and document results

Task 400 - Performance/Interface Requirements. Define performance requirements and system interfaces (e.g., sewage sludge feed, utilities, product disposition) for Phase III testing.

1. Prepare Phase III PFD and M&EBs for subsystems and integrated system, and verify projections for economically viable, large-scale systems.
2. Define interface requirements

Task 500 - Project management - Manage Phase II technical effort, budget, and schedule, and prepare Phase II report.

IV.A.2 Schedules, Milestones, and Decision Points

Fig. IV-1 presents the schedule, milestones and decision points for proposed Phase II activities. Contract award is assumed to occur April 1, 1998.

IV.B PHASE III - TECHNOLOGY VALIDATION

IV.B.1 Work Scope and Task Plans

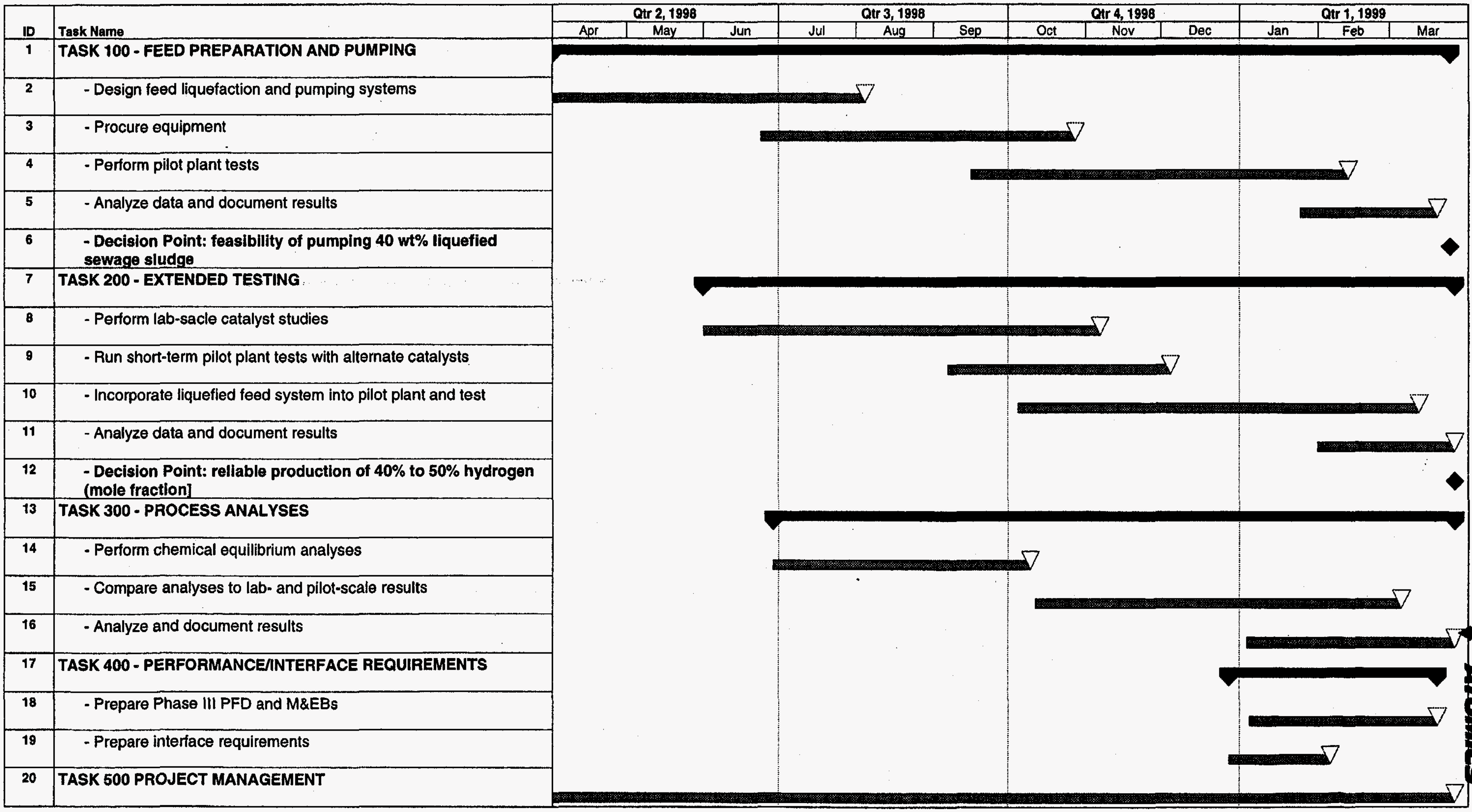
Phase III will consist of a subsystem validation effort including design, procurement and assembly of skid-mounted subsystems. Each subsystem will then undergo shakedown testing as a prelude to the Phase IV Integrated Pilot-Scale Demonstration. Safety analyses, reliability and maintainability studies, permitting studies, process control definition and updated life-cycle-cost analyses will also be performed.

Task 100 - Systems Analyses. Prepare systems analysis studies.

1. Perform safety analyses. Define hazards and hazard categories and design changes to mitigate unacceptable hazards.
2. Perform reliability, availability, and maintainability (RAM) analysis
3. Perform permitting study
4. Prepare updated life-cycle cost analysis
5. Decision point: identify potential barriers to commercialization

FIG. IV-1

SCHEDULE, MILESTONES AND DECISION POINTS FOR PHASE II



GENERAL ATOMICS

Task 200 - Systems Design. Prepare 5 MT/day equipment drawings and specifications, and define facility and support requirements

1. Define P&IDs and control logic diagrams
2. Prepare equipment drawings and specifications
3. Define vendor-supplied equipment and components, including membrane separators, PSA, etc.
4. Define pilot plant test area upgrades and support needs
5. Prepare fabrication/installation drawings
6. Decision point: verify availability of materials/equipment/components

Task 300 - Equipment Procurement/Assembly/Test. Procure 5 MT/day equipment and assemble as skid-mounted subsystems. Test subsystems.

1. Procure/refurbish SCWG components
2. Prepare skids and assemble subsystem components.
3. Perform subsystems testing.
4. Acquire support components for Phase IV (membrane unit, PSA, etc.)

Task 400 - Project Management

IV.B.2 Schedules, Milestones, and Decision Points

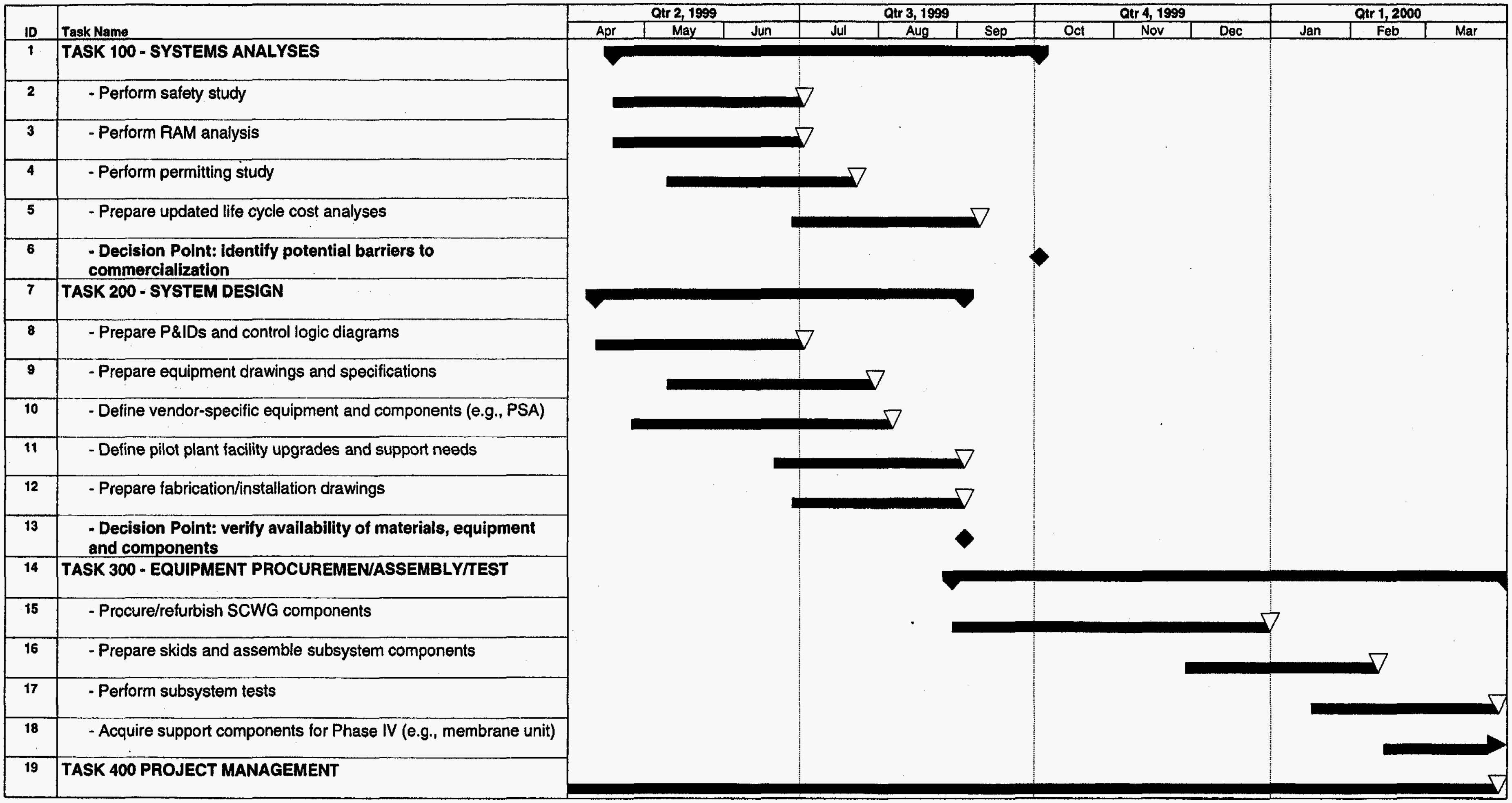
Fig. VI-2 presents the schedule, milestones and decision points for proposed Phase III activities. Contract award is assumed to occur April 1, 1999.

IV.C PHASE IV - DEMONSTRATION OF SCALE-UP

IV.C.1 Work Scope and Task Plans

The Phase IV effort will be directed at demonstrating gasification in the integrated pilot-scale SCWG system. Plant throughput will be approximately 10 times that of the existing GA SCWG pilot plant, but some existing GA-owned SCWO components may be used to reduce the costs for a 5 MT/day system. The skid-mounted subsystem modules, including the feed system, preheat system, gasifier, letdown system, and gas/liquid separator, will be combined with leased membrane separation and PSA units. Hydrogen storage and fuel cells are an optional component of this phase. The fuel cell size will be about 200 kW, a size available from a number of manufacturers.

FIG. IV-2
SCHEDULE, MILESTONES AND DECISION POINTS FOR PHASE III



Task 100 - Procurement. Procure remaining system components and equipment

1. Acquire balance-of-plant equipment and materials

Task 200 - System Assembly. Integrate the SCWG subsystems and prepare facility.

1. Assemble subsystems for integrated operation.
2. Program software for integrated operations.
3. Prepare pilot plant facility

Task 300 - System Checkout. Begin testing of major system components

1. Perform SCWG checkout tests with simulants
2. Perform SCWG checkout tests with sewage sludge

Task 400 - Integrated Testing. Complete testing of integrated SCWG system verifying hydrogen production and system reliability.

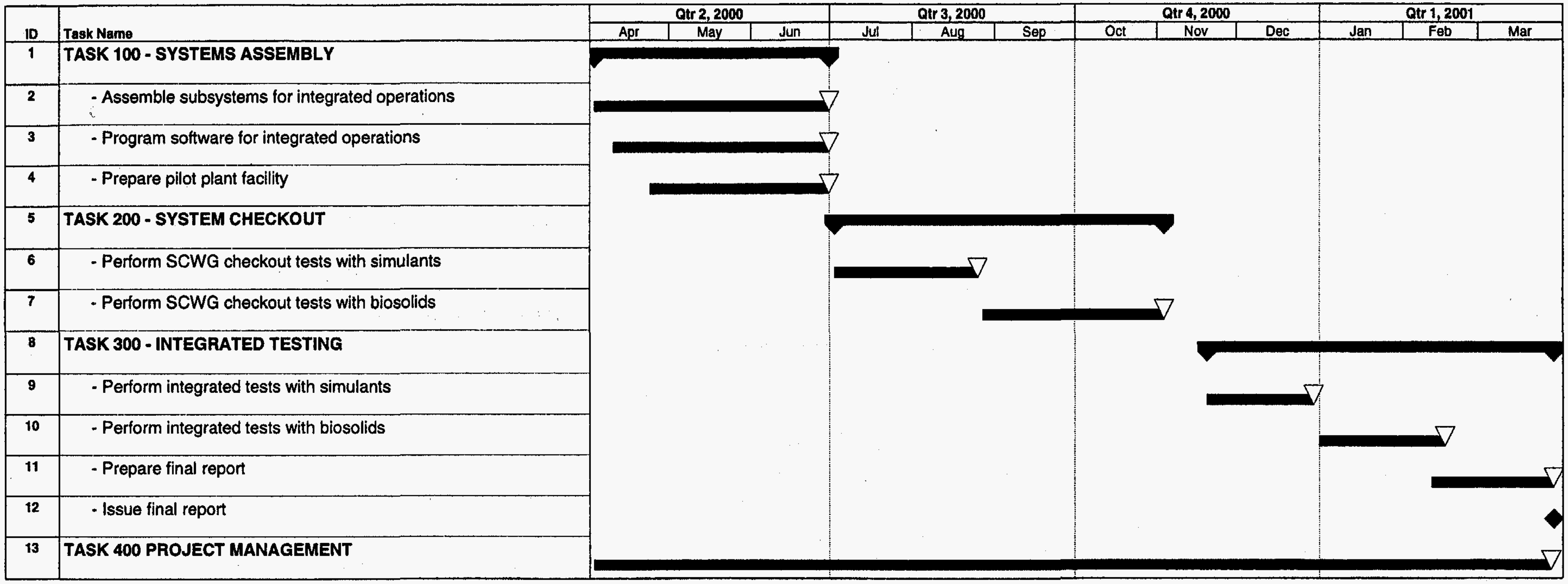
1. Perform SCWG integrated tests with simulants
2. Perform SCWG integrated tests with sewage sludge
3. Prepare and issue final report

Task 500 - Project Management

IV.C.2 Schedules, Milestones, and Decision Points

Fig. presents the schedule, milestones and decision points for proposed Phase III activities. Contract award is assumed to occur April 1, 2000.

FIG. IV-3
SCHEDULE, MILESTONES AND DECISION POINTS FOR PHASE IV



ID	Task Name
1	**TASK 100 - SYSTEMS ASSEMBLY**
2	- Assemble subsystems for integrated operations
3	- Program software for integrated operations
4	- Prepare pilot plant facility
5	**TASK 200 - SYSTEM CHECKOUT**
6	- Perform SCWG checkout tests with simulants
7	- Perform SCWG checkout tests with biosolids
8	**TASK 300 - INTEGRATED TESTING**
9	- Perform integrated tests with simulants
10	- Perform integrated tests with biosolids
11	- Prepare final report
12	- Issue final report
13	**TASK 400 PROJECT MANAGEMENT**

V. TEAMING AGREEMENTS FOR PHASES II - IV

GA will continue as the team leader for the follow-on phases. In addition, the Encina Wastewater Authority will continue the role it played in Phase I as an interested party to the development of SCWG for hydrogen production. The following sections describe the GA team, its capabilities, qualifications and experience, and facilities and equipment.

V.A TEAM MEMBERS AND RATIONALE FOR SELECTION

GA is one of the leading advanced technology companies in the U.S. with over 40 years of experience in science-oriented research and development as well as engineering development. GA facilities include engineering, test, manufacturing, and advanced technology laboratories. Phase 1 pilot plant studies were performed at the GA SCW facility. The proposed work for Phases II through IV will also be performed at GA. We have extensive experience in the use of our facilities in the design and testing of pilot- and full-scale equipment in accordance with DoD and other Government standards. The SCWG project is being conducted by the Advanced Process Systems (APS) Division of the Advanced Technologies Group. The project will continue to receive high visibility within the GA corporate organization. The Program Manager will continue to report directly to the Director of the APS Division, who, in turn, reports directly to the Senior Vice President for Advanced Technologies.

GA continues its major SCWO program, with over $20 million in contracts over the past five years. GA brings demonstrated experience in the management and execution of SCWO, and hazardous waste activities, including development and demonstration of concepts, technologies, and leading edge hardware.

Encina Wastewater Authority, located just north of GA, has been an important contributor to Phase I of the project and maintains a continuing interest in the effort to commercial sewage sludge gasification and hydrogen production. They operate a state-of-the-art facility serving over 225,000 residents in a location directly adjacent to the Pacific Ocean. They have an excellent reputation in the wastewater treatment industry as a well-run, progressive facility. In addition, they have exceptionally good relations with their customers, a fact that is especially noteworthy given high population density surrounding the plant and environmental sensitivity of nearby residents.

V.B TEAM MEMBER CAPABILITIES

GA is one of the largest privately owned centers for diversified research, development, and engineering in the world. GA is engaged in broad scope research, development, and production, with activities embracing research and development programs for power generation systems, energy conversion systems, waste management, environmental restoration, DoD and DOE programs, and other science-based technologies. Personnel with many years of experience in advanced science and engineering programs make up the various technical groups. Over half of the U.S.-based staff hold technical degrees; of these, more than half have advanced degrees.

GA currently has four Government-sponsored projects underway in SCWO of toxic and hazardous materials, two for DARPA and two for the U.S. Air Force. Completed SCWO projects include one for the Defense Advanced Research Projects Agency (DARPA), several for DOE and one for the National Aeronautics and Space Administration (NASA). GA has also licensed its SCWO technology to two other firms. GA has a well-qualified staff of engineers and technicians needed to design, build, and test SCWG systems of any size from bench-scale test rigs to commercial systems.

Encina provides a reliable source of primary and secondary sludge, skilled personnel, and the infrastructure needed to support an on-site demonstration of the SCWG system. Other municipal waste water treatment facilities have similar capabilities.

V.C QUALIFICATION AND EXPERIENCE OF KEY PERSONNEL

Key personnel in Phase I of the SCWG effort will continue throughout Phases II through IV. Dr. Dan Jensen will remain as the Project Manager. He brings over 25 years experience in the science- and engineering-based research and development, and over 10 years experience in managing large tasks and projects. He was the Deputy Project Manager for the initial $6.8 million DARPA contract to develop SCWO for the treatment of chemical warfare agent and was the on-site project manager for the design, equipment procurement, construction and checkout of a comprehensive conventional munitions disposal facility located south of Berlin, Germany

Dr. David Hazlebeck is a key technical lead on all of GA's SCWO projects and will continue in this role with the SCWG program. He brings over 10 years of experience in the design and testing of chemical process equipment and SCW systems. He is currently the Project Manager for the DARPA-sponsored effort leading to a modular, highly compact SCWO system for the treatment of excess hazardous materials onboard Naval vessels.

Mr. Kevin Downey was the lead process engineer during Phase I SCWO and SCWG testing and will continue in this role in subsequent phases. He brings over 15 years experience in the design and testing of systems for the treatment and disposal of waste materials and the startup of advanced chemical process systems.

Dr. Glenn Hong, a consultant for GA, has been a key member of the Phase I SCWG design and analysis team. He brings over 20 years experience derived from his pioneering role in helping develop SCWO as a near-commercial business, including the receipt of numerous SCWO-related patents. He will continue to provide his first-hand knowledge of the chemical process industry to the Phase II through IV effort as analysis of test data and design of the pilot plant evolve.

At present, none of the Encina staff will be expected to play a key role in the program. The primary interface will continue to be Mr. Paul Bushee.

V.D TEAM MEMBER FACILITIES AND EQUIPMENT

GA provides the complete spectrum of facilities to design, build, and test SCWG equipment utilized during Phase I of the project. GA has a materials engineering facility with extensive capabilities for subcritical and supercritical fluid systems, corrosion and solid/fluid flow testing, metals and ceramics, research and joining/fabrication technology along with complete familiarity with all associated specifications, codes and standards. Analyses of stress corrosion, erosion, and high temperature gaseous corrosion can be performed with the aid of metallurgical diagnostics.

GA has manufacturing facilities used to fabricate specialized components and systems for military applications to ASME codes, including a documented quality assurance system. We also has developed a network of manufacturing subcontractors throughout Southern California capable of performing any processes required in the construction of advanced, high-technology systems.

Phase I SCWG studies were performed in the pilot-scale facility located in San Diego previously used for a broad range of SCWO tests. This system will continue to be used for pilot-scale testing during proposed Phase II testing. During Phases III and IV, the pilot plant will be reconfigured as needed to accommodate the larger throughput planned for these stages of testing. This will include a larger gasifier vessel and related components as needed.

Encina has facilities that could be used to house the SCWG systems. Space is available in several buildings near the sludge processing area that could house the SCWG equipment and interface with the existing sludge treatment works.

V.E TEAM MEMBER STATEMENTS OF COMMITMENT

GA views renewable energy sources as vital to power generation in the decades to come and is committed to their development for the generation of hydrogen. In addition, Encina Wastewater Authority has indicated its continuing interest in the program for hydrogen generation via SCWG of sewage sludge. We look forward to the opportunity to continuing this effort together with the DOE in the development of SCWG for production of hydrogen from biomass fuels.

ENCINA
WASTEWATER
AUTHORITY
Serving
North San Diego
County

ENCINA WASTEWATER AUTHORITY
A Public Agency

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December 17, 1997

Ref: 3518

General Atomics
P.O. Box 85608
San Diego, CA 92138-9784

Attention: Dr. Dan Jensen

SUBJECT: Supercritical Water Gasification of Wastewater Biosolids

Earlier in the year the Encina Wastewater Authority (EWA) provided primary and secondary biosolids for use in General Atomics' (GA) pilot plant supercritical waste oxidation (SCWO) and SCWG studies. We recently met to discuss the results for both the SCWO workup tests and SCWG runs for hydrogen production.

The EWA's facility uses a variety of advanced treatment technologies to process the wastewater from over 225,000 residents in our service area, while recovering energy where possible. In the future, we believe that SCWG could potentially provide both an economical means of treating wastewater in an environmentally friendly manner and serve as a reliable means of producing hydrogen for on-site power production or off-site sale.

In light of this, we would like to express our continuing interest in the development of SCWG as a potential alternate means of processing both biosolids feed and solids effluent. If you have any questions please do not hesitate to contact me at (760) 727-3614 or E
-mail me at "PAUL@Encinajpa.com".

Very truly yours,

Paul Bushee
Resource Reclamation Specialist

PB:lc

xc: John Murk, EWA General Manager
Mike Hogan, EWA Director of Operations
Mike Fileccia, EWA Technical Services Director

SERVING THE CITY OF VISTA, CITY OF CARLSBAD, BUENA SANITATION DISTRICT, VALLECITOS WATER DISTRICT,
LEUCADIA COUNTY WATER DISTRICT AND CITY OF ENCINITAS

VI. RESOURCE REQUIREMENTS FOR PHASES II - IV

Resource requirements for Phases II through IV were developed from the proposed project planning described in Sec. IV. Personnel, equipment, materials, supplies and other requirements were defined. These were then integrated into budgets for each phase and funding requirements defined.

VI.A PERSONNEL

Table VI-1 shows the personnel staffing requirements for each phase of the project. Key personnel discussed in Sec. VC will be assisted by staff personnel at GA.

Table VI-1. Personnel Requirements for Phases II through IV

Position Title	Phase II Man-hours	Phase III Man-hours	Phase IV Man-hours	Total Man-hours
Technical Staff	7040	15,920	5760	28,720
Project Management	480	1440	480	2400

VI.B EQUIPMENT, MATERIALS, AND SUPPLIES

Table VI-2 presents a list of equipment, materials and supplies required for Phases II through IV.

VI.C OTHER RESOURCE REQUIREMENTS

Other resources include the GA pilot plant and supporting facilities, utilities, computer control system, sewage sludge receiving/holding equipment and related items.

Table VI-2. Required Equipment, Materials and Supplies

Phase	Item
II	Sewage sludge press
	Sewage sludge liquefaction components
	Updated pumping system components
	Laboratory supplies
	Analytical services
III	Updated liquefaction/pumping system components
	Gas-fired trim heater
	New or altered GA SCW gasifier
	Heat recovery heat exchanger and waste heat boiler
	Refurbished gas/solid separator
	Analytical services
IV	Leased membrane and PSA units
	Analytical services

VI.D TOTAL BUDGET ESTIMATE

Table VI-3 presents the budgetary estimate for Phases II through IV based on the proposed scope of work are as follows

Table VI-3. 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

VI.E DOE FUNDING REQUIREMENTS AND CONSORTIUM COST SHARE

Table VI-4 presents the DOE and GA Team funding requirements for Phases II through IV.

Table VI-4. 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

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APPENDIX A
M&EBS FOR 20 AND 40 WT% BIOSOLIDS

MASS AND ENERGY BALANCE FOR 27 MT/DAY SCWG SYSTEM, 20% BIOSOLIDS, HIGHER HYDROGEN YIELDS

SCWG Mass and Energy Balance				**Plant size =**		**30**	**tpd combustible biosolids**										
Liquefied sludge solids, wt%		**20**				**39.6**	**tpd total biosolids**										
Stream No.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**
Stream Name	Biosolids Feed	Liquefier Ash Purge	Liquefier Sludge	Pre-heated Sludge	Reactor Feed	Reactor Effluent	Partially Cooled Effluent	Cooled Effluent	Liquid + Solid Effluent	High Pressure Gas	Medium Pressure Gas	Membrane Fuel Gas	Membrane H2	PSA Fuel Gas	Mixed Fuel Gas	PSA H2	Storage H2
Parameter:																	
Temperature, C	25	200	200	444	650	650	296	40	40	40	25	25	25	25	25	25	25
Pressure, psia	14.7	3400	3400	3400	3400	3400	3400	3400	3400	3400	1950	20	500	20	20	500	200
Mass flow, kg/sec	1.8	0.2	1.6	1.6	1.6	1.6	1.6	1.6	1.2	0.4	0.4	0.3	0.2	0.2	0.4	0.0	0.0
Heat flow, MWatts	0.0	0.0	1.1	2.7	0.94	0.0	-2.71	-1.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Solids, kg/sec	0.42	0.10	0.32	0.32	0.32	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
H2O, kg/sec	1.36	0.10	1.26	1.26	1.26	1.08	1.08	1.08	1.08	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
H2, kg/sec	0.00	0.00	0.00	0.00	0.00	0.03	0.03	0.03	0.00	0.03	0.03	0.00	0.03	0.01	0.01	0.02	0.02
CO, kg/sec	0.00	0.00	0.00	0.00	0.00	0.02	0.02	0.02	0.00	0.02	0.02	0.01	0.01	0.01	0.02	0.00	0.00
CO2, kg/sec	0.00	0.00	0.00	0.00	0.00	0.40	0.40	0.40	0.06	0.34	0.34	0.20	0.13	0.13	0.34	0.00	0.00
CH4, kg/sec	0.00	0.00	0.00	0.00	0.00	0.04	0.04	0.04	0.00	0.04	0.04	0.03	0.00	0.00	0.04	0.00	0.00

Assumptions:		
For gaseous reaction products, use Antal 9/97 yields on poplar/corn starch.		
Reaction assumed to be thermally neutral.		
All available fuel gas burned in trim heater.		
Heat losses from reactor and lines ignored.		
Heat capacity of nonwater constituents approximated as 1 J/g/K.		
Gas fired heater efficiency, %	30	
Concentrated sludge solids, wt%	23	(before liquefier)
Noncombustible content of sludge solids, wt%	25	(before liquefier)
Liquefied sludge solids, wt%	20	(after liquefier)
Noncombustible content of sludge solids, wt%	1	(after liquefier)
Ash purge from liquefier is 50% solids.		

Regen HX balance

T guess	dH(G&S)	H(H2O)	MW
296	-173.6	1311.8	-2.709

Lower Heating Value of Fuel Gas

Gas	Hc, kcal/mol	MW
H2	57.8	1.0
CO	67.6	0.2
CH4	192	1.9
Total		3.1

Fired heater balance

T guess	dH(G&S)	H(H2O)	MW
444	0.1	2954.6	0.940

Excess enthalpy in steam loop

0.27	MW

H2 Production

772,010	scfd
770,000	scfd for this size plant in M.K. Mann study of Batelle gasifier (woody biomass)

Stream 8 CO2
partial pressure

34	mol%
79	atm

Stream 11 mol%

H2	57.0
CO	3.2
CO2	30.3
CH4	9.5
Total	100.0

Stream 13 mol%

H2	78.2
CO	1.9
CO2	18.4
CH4	1.5
Total	100.0

Stream 15 mol%

H2	27.1
CO	5.4
CO2	51.4
CH4	16.2
Total	100.0

H2 MW Equivalent
2.4

GENERAL ATOMICS

MASS AND ENERGY BALANCE FOR 27 MT/DAY SCWG SYSTEM, 40% BIOSOLIDS, HIGHER HYDROGEN YIELDS

SCWG Mass and Energy Balance				**Plant size =**		30	**tpd combustible biosolids**											
Liquefied sludge solids, wt%		40				39.6	**tpd total biosolids**											
Stream No.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	
Stream Name	Biosolids Feed	Liquefier Ash Purge	Liquefier Sludge	Pre-heated Sludge	Reactor Feed	Reactor Effluent	Partially Cooled Effluent	Cooled Effluent	Liquid + Solid Effluent	High Pressure Gas	Medium Pressure Gas	Membrane Fuel Gas	Membrane H2	PSA Fuel Gas	Mixed Fuel Gas	PSA H2	Storage H2	
Parameter:																		
Temperature, C	25	200	200	372	650	650	383	40	40	40	25	25	25	25	25	25	25	
Pressure, psia	14.7	3400	3400	3400	3400	3400	3400	3400	3400	3400	1950	20	500	20	20	500	200	
Mass flow, kg/sec	1.0	0.2	0.8	0.8	0.8	0.8	0.8	0.8	0.3	0.5	0.5	0.3	0.2	0.2	0.4	0.0	0.0	
Heat flow, MWatts	0.0	0.0	0.5	0.5	0.94	0.0	-0.52	-0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Solids, kg/sec	0.42	0.10	0.32	0.32	0.32	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
H2O, kg/sec	0.57	0.10	0.47	0.47	0.47	0.30	0.30	0.30	0.30	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	
H2, kg/sec	0.00	0.00	0.00	0.00	0.00	0.03	0.03	0.03	0.00	0.03	0.03	0.00	0.03	0.01	0.01	0.02	0.02	
CO, kg/sec	0.00	0.00	0.00	0.00	0.00	0.02	0.02	0.02	0.00	0.02	0.02	0.01	0.01	0.01	0.02	0.00	0.00	
CO2, kg/sec	0.00	0.00	0.00	0.00	0.00	0.40	0.40	0.40	0.02	0.38	0.38	0.23	0.15	0.15	0.38	0.00	0.00	
CH4, kg/sec	0.00	0.00	0.00	0.00	0.00	0.04	0.04	0.04	0.00	0.04	0.04	0.03	0.00	0.00	0.04	0.00	0.00	
	*	*	*															
								Regen HX balance					Stream 8 CO2			Stream 15 mol%		
Assumptions:								T guess	dH(G&S)	H(H2O)	MW		partial pressure			H2	25.3	
For gaseous reaction products, use Antal 9/97 yields on poplar/corn starch.								383	-130.9	2327.7	-0.524		34	mol%		CO	5.1	
Reaction assumed to be thermally neutral.													79	atm		CO2	54.5	
All available fuel gas burned in trim heater.								Lower Heating Value of Fuel Gas								CH4	15.1	
Heat losses from reactor and lines ignored.								Gas	Hc, kcal/mol	MW			Stream 11 mol%			Total	100.0	
Heat capacity of nonwater constituents approximated as 1 J/g/K.								H2	57.8	1.0			H2	54.8				
Gas fired heater efficiency, %				30				CO	67.6	0.2			CO	3.1		H2 MW Equivalent		
Concentrated sludge solids, wt%				42	(before liquefier)			CH4	192	1.9			CO2	33.0		2.4		
Noncombustible content of sludge solids, wt%				25	(before liquefier)			Total		3.1	*		CH4	9.2				
Liquefied sludge solids, wt%				40	(after liquefier)								Total	100.0				
Noncombustible content of sludge solids, wt%				1	(after liquefier)			Fired heater balance										
Ash purge from liquefier is 50% solids.								T guess	dH(G&S)	H(H2O)	MW		Stream 13 mol%					
								372	0.1	1841	0.942		H2	76.3				
													CO	1.9				
								Excess enthalpy in steam loop					CO2	20.4				
								0.31	MW				CH4	1.4				
													Total	100.0				
								H2 Production										
								772,010	scfd									
								770,000	scfd for this size plant in M.K. Mann study of Batelle gasifier (woody biomass)									

STEAM BALANCES FOR 27 MT/DAY SYSTEM, HIGHER HYDROGEN YIELDS

SCWG Steam Production		Plant size =	30	tpd municipal sewage sludge solids			18:12	30-Dec-97	GTH	
1200 psig steam						DDJ				
Tsat = 569F or 298C	Case	20%	40%							
Liquefier loop steam recovery:				Trim heater gas analysis		Air In		Partial P	40C Pvap	
Available MW		0.27	0.31	Gas	Fuel Gas In	(100% excess)	Off Gas	psia	psia	
1200 psig steam, kg/sec		0.10	0.11	H2O	0.00		0.16	1.31	1.07	
1200 psig steam, kg/kg dry biomass		0.32	0.36	H2	0.01					
				CO	0.02					
Flue Gas steam recovery				CO2	0.38		0.52			
Available MW		2.14	2.14	CH4	0.04					
1200 psig steam, kg/sec		0.77	0.77	O2		0.46	0.23			
1200 psig steam, kg/kg dry biomass		2.46	2.46	N2		1.98	1.98			
				Total kg/sec	0.45	2.44	2.89			
Total 1200 psig steam recovery:		2.77	2.82	MW, 25C to 40C			0.05			
MMBtu/day		198	201							
Annual credit		$ 294,020	$ 298,476							
M. Mann Steam, kg/kg dry biomass			Heating stream	Heating stream	Heating stream	Heating stream	Steam	Steam	Steam	Steam
Location	psig	Amount	Initial T, C	Final T, C	Initial T, F	Final T, F	Initial T, C	Final T, C	Initial T, F	Final T, F
Between shift reactors	500	0.32	434.8	200.0	815	392	17.3	254.5	63	490
Fuel cell	100	1.26	203.3		398					
Air compression	100	0.12	212.7	189.3	415	373				
Combustor flue gas	100	0.43	238.3	27.8	461	82	15.4	182.2	60	360
Gas to PSA	100	0.85	221.0	23.9	430	75	15.4	204.2	60	400
Checking M.Mann Steam Generation Calcs					276.564					
Location	psig	Btu/hr/lb of wood	Steam Btu/lb	lb steam/lb wood						
Between shift reactors	500	365.5	1194	0.31	46.094					
Syngas compression	100	1530	1178	1.30	92.188					
Air compression	100	131.3	1178	0.11						
Combustor flue gas	100	485.3	1178	0.41						
Gas to PSA	100	967.7	1199	0.81						
Steam credits										
M. Mann										
500 psi	$3.57	/1000 lb	$ 4.73	/MMBtu						
100 psi	$2.35	/1000 lb	$ 3.12	/MMBtu						
Modell 1990										
1200 psi	$5	/MMBtu								
600 psi	$4	/MMBtu								
150 psi	$3	/MMBtu								

GENERAL ATOMICS

MASS AND ENRGY BALANCE FOR 27 MT/DAY SCWG SYSTEM, 20% BIOSOLIDS, LOWER HYDROGEN YIELDS

SCWG Mass and Energy Balance				**Plant size =**		**30**	**tpd combustible biosolids**											
Liquefied sludge solids, wt%		**20**				**39.6**	**tpd total biosolids**											
Stream No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	
Stream Name	Biosolids Feed	Liquefier Ash Purge	Liquefier Sludge	Pre-heated Sludge	Reactor Feed	Reactor Effluent	Partially Cooled Effluent	Cooled Effluent	Liquid + Solid Effluent	High Pressure Gas	Medium Pressure Gas	Membrane Fuel Gas	Membrane H2	PSA Fuel Gas	Mixed Fuel Gas	PSA H2	Storage H2	
Parameter:																		
Temperature, C	25	200	200	445	650	650	327	40	40	40	25	25	25	25	25	25	25	
Pressure, psia	14.7	3400	3400	3400	3400	3400	3400	3400	3400	3400	1950	20	500	20	20	500	200	
Mass flow, kg/sec	1.8	0.2	1.6	1.6	1.6	1.6	1.6	1.6	1.3	0.3	0.3	0.2	0.1	0.1	0.3	0.0	0.0	
Heat flow, MWatts	0.0	0.0	1.1	2.7	0.93	0.0	-2.72	-1.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Solids, kg/sec	0.42	0.10	0.32	0.32	0.32	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
H2O, kg/sec	1.36	0.10	1.26	1.26	1.26	1.20	1.20	1.20	1.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
H2, kg/sec	0.00	0.00	0.00	0.00	0.00	0.02	0.02	0.02	0.00	0.02	0.02	0.00	0.01	0.00	0.00	0.01	0.01	
CO, kg/sec	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
CO2, kg/sec	0.00	0.00	0.00	0.00	0.00	0.30	0.30	0.30	0.07	0.23	0.23	0.14	0.09	0.09	0.23	0.00	0.00	
CH4, kg/sec	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.00	0.05	0.05	0.05	0.01	0.01	0.05	0.00	0.00	
							Same as 100 MTD SCWO Pla	Regen HX balance					Stream 8 CO2			Stream 15 mol%		
Assumptions:								T guess	dH(G&S)	H(H2O)	MW		partial pressure			H2	19.9	
For gaseous reaction products, use Antal 9/97 yields on poplar/corn starch.								327	-121.1	1482.1	-2.722		39	mol%		CO	0.8	
Reaction assumed to be thermally neutral.													89	atm		CO2	49.5	
All available fuel gas burned in trim heater.								Lower Heating Value of Fuel Gas								CH4	29.8	
Heat losses from reactor and lines ignored.								Gas	Hc, kcal/mol	MW			Stream 11 mol%			Total	100.0	
Heat capacity of nonwater constituents approximated as 1 J/g/K.								H2	57.8	0.5			H2	47.0				
Gas fired heater efficiency, %				30				CO	67.6	0.0			CO	0.5		H2 MW Equivalent		
Concentrated sludge solids, wt%				23	(before liquefier)			CH4	192	2.6			CO2	32.7		1.3		
Noncombustible content of sludge solids, wt%				25	(before liquefier)			Total		3.1			CH4	19.7				
Liquefied sludge solids, wt%				20	(after liquefier)								Total	100.0				
Noncombustible content of sludge solids, wt%				1	(after liquefier)			Fired heater balance										
Ash purge from liquefier is 50% solids.								T guess	dH(G&S)	H(H2O)	MW		Stream 13 mol%					
								445	0.1	2959.6	0.933		H2	73.5				
													CO	0.4				
								Excess enthalpy in steam loop					CO2	22.7				
								0.59	MW				CH4	3.4				
													Total	100.0				
								H2 Production										
								411,179	scfd									
								770,000	scfd for this size plant in M.K. Mann study of Batelle gasifier (woody biomass)									

MASS AND ENERGY BALANCE FOR 27 MT/DAY SCWG SYSTEM, 40% BIOSOLIDS, LOWER HYDROGEN YIELDS

SCWG Mass and Energy Balance				**Plant size =**		**30**	**tpd combustible biosolids**					17:56						
Liquefied sludge solids, wt%		40				39.6	**tpd total biosolids**											
Stream No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	
Stream Name	Biosolids Feed	Liquefier Ash Purge	Liquefier Sludge	Pre-heated Sludge	Reactor Feed	Reactor Effluent	Partially Cooled Effluent	Cooled Effluent	Liquid + Solid Effluent	High Pressure Gas	Medium Pressure Gas	Membrane Fuel Gas	Membrane H2	PSA Fuel Gas	Mixed Fuel Gas	PSA H2	Storage H2	
Parameter:																		
Temperature, C	25	200	200	373	650	650	395	40	40	40	25	25	25	25	25	25	25	
Pressure, psia	14.7	3400	3400	3400	3400	3400	3400	3400	3400	3400	1950	20	500	20	20	500	200	
Mass flow, kg/sec	1.0	0.2	0.8	0.8	0.8	0.8	0.8	0.8	0.44	0.3	0.3	0.2	0.1	0.1	0.3	0.0	0.0	
Heat flow, MWatts	0.0	0.0	0.5	0.5	0.934	0.0	-0.525	-1.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Solids, kg/sec	0.42	0.10	0.32	0.32	0.32	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
H2O, kg/sec	0.57	0.10	0.47	0.47	0.47	0.41	0.41	0.41	0.41	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
H2, kg/sec	0.00	0.00	0.00	0.00	0.00	0.02	0.02	0.02	0.00	0.02	0.02	0.00	0.01	0.00	0.00	0.01	0.01	
CO, kg/sec	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
CO2, kg/sec	0.00	0.00	0.00	0.00	0.00	0.30	0.30	0.30	0.02	0.28	0.28	0.17	0.11	0.11	0.28	0.00	0.00	
CH4, kg/sec	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.00	0.05	0.05	0.05	0.01	0.01	0.05	0.00	0.00	
	*	*	*															
							Same as 100 MTD SCWO Pla	Regen HX balance					Stream 8 CO2			Stream 15 mol%		
Assumptions:								T guess	dH(G&S)	H(H2O)	MW		partial pressure			H2	18.2	
For gaseous reaction products, use Antal 9/97 yields on poplar/corn starch.								395	-95.6	2606.9	-0.526		39	mol%		CO	0.8	
Reaction assumed to be thermally neutral.													89	atm		CO2	53.9	
All available fuel gas burned in trim heater.								Lower Heating Value of Fuel Gas								CH4	27.2	
Heat losses from reactor and lines ignored.								Gas	Hc, kcal/mol	MW			Stream 11 mol%			Total	100.0	
Heat capacity of nonwater constituents approximated as 1 J/g/K.								H2	57.8	0.5			H2	44.2				
Gas fired heater efficiency, %				30				CO	67.6	0.0			CO	0.5		H2 MW Equivalent		
Concentrated sludge solids, wt%				42	(before liquefier)			CH4	192	2.6			CO2	36.7		1.3		
Noncombustible content of sludge solids, wt%				25	(before liquefier)			Total		3.1	*		CH4	18.5				
Liquefied sludge solids, wt%				40	(after liquefier)								Total	100.0				
Noncombustible content of sludge solids, wt%				1	(after liquefier)			Fired heater balance										
Ash purge from liquefier is 50% solids.								T guess	dH(G&S)	H(H2O)	MW		Stream 13 mol%					
								373	0.1	1857.1	0.934		H2	70.4				
													CO	0.4				
								Excess enthalpy in steam loop					CO2	26.0				
								0.64	MW				CH4	3.3				
													Total	100.0				
								H2 Production										
								411,179	scfd									
								770,000	scfd for this size plant in M.K. Mann study of Batelle gasifier (woody biomass)									

STEAM BALANCES FOR 27 MT/DAY SCWG SYSTEM, LOWER HYDROGEN YIELDS

SCWG Steam Production		Plant size =	30	tpd municipal sewage sludge solids			18:02	30-Dec-97	GTH	
1200 psig steam						DDJ				
Tsat = 569F or 298C	Case	20%	40%							
Liquefier loop steam recovery:				Trim heater gas analysis		Air In		Partial P	40C Pvap	
Available MW		0.59	0.64	Gas	Fuel Gas In	(100% excess)	Off Gas	psia	psia	
1200 psig steam, kg/sec		0.21	0.23	H2O	0.00		0.16	1.31	1.07	
1200 psig steam, kg/kg dry biomass		0.68	0.73	H2	0.01					
				CO	0.02					
Flue Gas steam recovery				CO2	0.38		0.52			
Available MW		-0.70	-0.70	CH4	0.04	Not required				
Available MW		2.13	2.13	CH4	0.04					
1200 psig steam, kg/sec		0.77	0.77	O2		0.46	0.23			
1200 psig steam, kg/kg dry biomass		2.45	2.45	N2		1.98	1.98			
				Total kg/sec	0.49	2.44	2.89			
Total 1200 psig steam recovery:		3.12	3.18	MW, 25C to 40C			0.05			
MMBtu/day		223	227							
Annual credit		$ 331,295	$ 337,075							
						Same as 100 MTD SCWO Plant				
M. Mann Steam, kg/kg dry biomass			Heating stream	Heating stream	Heating stream	Heating stream	Steam	Steam	Steam	Steam
Location	psig	Amount	Initial T, C	Final T, C	Initial T, F	Final T, F	Initial T, C	Final T, C	Initial T, F	Final T, F
Between shift reactors	500	0.32	434.8	200.0	815	392	17.3	254.5	63	490
Fuel cell	100	1.26	203.3		398					
Air compression	100	0.12	212.7	189.3	415	373				
Combustor flue gas	100	0.43	238.3	27.8	461	82	15.4	182.2	60	360
Gas to PSA	100	0.85	221.0	23.9	430	75	15.4	204.2	60	400
Checking M.Mann Steam Generation Calcs					276.564					
Location	psig	Btu/hr/lb of wood	Steam Btu/lb	lb steam/lb wood						
Between shift reactors	500	365.5	1194	0.31	46.094					
Syngas compression	100	1530	1178	1.30	92.188					
Air compression	100	131.3	1178	0.11						
Combustor flue gas	100	485.3	1178	0.41						
Gas to PSA	100	967.7	1199	0.81						
Steam credits										
M. Mann										
500 psi	$3.57	/1000 lb	$ 4.73	/MMBtu						
100 psi	$2.35	/1000 lb	$ 3.12	/MMBtu						
Modell 1990										
1200 psi	$5	/MMBtu								
600 psi	$4	/MMBtu								
150 psi	$3	/MMBtu								

GENERAL ATOMICS

APPENDIX B
TEST REPORT: SEWAGE SLUDGE GASIFICATION AND OXIDATION IN SUPERCRITICAL WATER

GENERAL
ATOMICS

TEST REPORT:
SEWAGE SLUDGE GASIFICATION IN SUPERCRITICAL WATER

GENERAL ATOMICS
P. O. BOX 85608
SAN DIEGO, CA 92186-9784

DECEMBER 1997

PREPARED FOR THE UNITED STATES
DEPARTMENT OF ENERGY
Under Cooperative Agreement
No. DE-FC36-97GO10216

LIST OF ACRONYMS

BOD	Biological oxygen demand
COD	Chemical oxygen demand
GA	General Atomics
HC	hydrocarbon
HCl	hydrochloric acid
MT	metric ton
NO_x	Nitrogen oxides
pg/g	picograms/gram
ppm	parts per million (1 part in 10^6)
SCW	Supercritical water
SCWG	Supercritical water gasification
SCWO	Supercritical water oxidation
SO_x	Sulfur oxides
TCLP	Toxicity Characteristic Leaching Procedure
TOC	Total organic carbon
TS	Total solids
TSS	Total suspended solid
VSS	Volatile suspended solids
VTS	Volatile total solids

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FIGURES

TABLES

1. INTRODUCTION

This report presents the results of sewage sludge gasification testing conducted at the General Atomics (GA) supercritical water (SCW) pilot plant during the period of April - November of 1997. Specific activities included the characterization of local municipal sewage sludge, preparation and performance of pumping tests, modification of the pilot plant feed system (to remove grit and to grind/emulsify the sewage sludge), definition and implementation of sewage sludge handling methods and devices (for personnel safety and odor control), performance of supercritical water oxidation (SCWO) workup tests with full and then partial oxidation of sewage sludge in combination with heat recovery and/or auxiliary fuel addition, and finally the production of a hydrogen-rich synthesis gas at high pressures and temperatures.

The supercritical water gasification (SCWG) tests generally verified the performance of laboratory tests conducted at the University of Hawaii at Manoa using a carbon catalyst bed, although the pilot plant tests yielded somewhat lower hydrogen concentrations and higher volatile hydrocarbon concentrations.

Section 2 presents the summary and conclusions for the test series. Section 3 discusses the tests that were conducted, the technical conclusions that were drawn from the data, and the technical uncertainties that still exist.

2. SUMMARY AND CONCLUSIONS

The conclusions GA has drawn from the test data are summarized below. In general, there are three qualifications that apply to all of the technical conclusions that should be kept in mind when the data are being interpreted.

1. The tests were generally of short duration (i.e., <8 hr for SCWO and <1.5 hr for SCWG), so long term reliability data were not obtained.
2. The test program included very few repeat tests, so the formal statistics are weak.
3. The test facility is of a reasonable size (up to 4 l/min) and provides good flexibility for the treatment of various feedstocks. However, it does have system limitations that prevented optimum sewage sludge gasification.

These qualifications imply that the data base that was developed, while valid and significant, is still incomplete, and all conclusions drawn should recognize this.

1. Sewage sludge with up to 10% solids could be pumped to operating pressure in a repeatable manner. The technique was to first macerate the feed and then use a proprietary high pressure pumping system to feed it to the SCW reactor. This combination worked well for 8-hr SCWO workup tests (performed to verify methods of sewage sludge preparation, sludge pumping and feeding to the reactor, and pressure letdown) and during shorter-duration SCWG tests.
2. Sewage sludge could be successfully pumped through the preheater piping to temperatures as high as 650°C. No signs of plugging were observed. Preheating was successfully demonstrated both with electric heat and with reactor exit heat recovery.
3. While the preheaters were capable of heating the sewage sludge feed to 650°C, the feed rate was limited to ~0.48 kg/min due to heater power constraints. Either more heater power or, more likely, some degree of heat recovery is required for higher throughputs.
4. Sewage sludge could be injected into the reactor through an existing GA-designed nozzle for extended periods without plugging.
5. Although no quantification was attempted, preheat of the sewage sludge feed to gasification temperatures (>600°C) will likely produce some degree of char that may

eventually cause plugging of the catalyst bed. Upon inspection of the bed following the gasification test of 11/24/97, some fine, char-like material was present at the inlet of the catalyst bed within the top 1 to 3 in.

6. Because of heat loss to the environment, the addition of tape heaters to the external reactor wall was necessary in order to maintain required temperatures.
7. The coconut shell carbon bed material selected for pilot plant testing was somewhat friable and prone to attrition and compaction. Relatively small reactor pressure fluctuations caused small fragments of bed material to fall through the bed support screen. Over time, the accumulation of bed material at the inlet of the pressure letdown valve resulted in a loss of system pressure control. A more robust bed material is needed.
8. The pressure letdown system functioned satisfactorily, but material erosion was a problem during extended SCWO workup tests that required certain parts to be replaced frequently. A more durable material or material coating should provide better performance. Removal of ash from the feed will also reduce erosion.
9. Liquid effluent TOC levels were approximately 1500 to 1700 ppm, indicating a TOC destruction of ~94% from the initial concentration in the sewage sludge of ~26,500 ppm. Further process optimization is required for complete TOC destruction.
10. The hydrogen concentration in the gaseous effluent was approximately 25 volume %, somewhat lower than laboratory-scale tests which yielded concentrations of 33% (Ref. 1). The difference is due mostly to the presence of significant quantities of higher molecular weight hydrocarbons (generally C_2 to C_6) in the pilot plant tests that were not found in high concentration in the laboratory tests.
11. The estimated conversion of carbon to volatile carbon-containing species was 94% (by wt%). The estimated conversion of hydrogen to H_2 gas was 28.5%. Much of the hydrogen remained bonded in organic species, principally methane, ethane, and propane.

3. TEST RESULTS

A series of SCWO workup tests and SCWG tests were carried out with sewage sludge in GA's SCW pilot plant. The purpose of the tests was to verify laboratory-scale results, define pilot plant design operating conditions, determine areas of technical uncertainty, and establish parameters for the economic assessment of commercial-scale units. Table 3-1 summarizes the key features of the tests. Feed material and effluent sampling and analyses were performed during workup tests and during all sewage sludge feed tests. Operating data were collected during all tests with the pilot plant automated data acquisition system.

Figure 3-1 shows as-received and blended sewage sludge feed, SCWO reactor effluent immediately after discharge, and effluent after ~1 to 2 hr to allow time for settling of particulates. Figure 3-2 shows similar materials for the SCWG tests. These results are typical of those found during tests performed at optimized conditions.

The following sections describe the waste feed characteristics and key findings of the tests.

3.1. FEED CHARACTERISTICS OF SEWAGE SLUDGE

Primary and secondary sewage sludge was provided by the Encina Wastewater Authority in Carlsbad, California, located approximately 10 miles north of GA. The Encina plant treats the sewage for a population base of approximately 225,000 people and generates 90-100 MT/day of treated secondary waste at ~17 to 18 wt% solids. Table 3-3 presents minimum, mean and maximum values for various batches of the Encina primary and secondary sludge. Data are presented for TOC, total solids (TS), total suspended solids (TSS), volatile total solids (VTS), volatile suspended solids (VSS), and heavy metals content.

TABLE 3-1
TEST MATRIX FOR SCWO WORKUP TESTS

Test No.	Feed Type	Sludge Feed Rate (kg/min)	Temperature (°C)	Pressure (psi)	Test Date	Comments
1	Sludge at 0.5 wt%	0.32	650	23.4	4/21/97	Initial test of sludge processing
2	Sludge at 0.5 wt%	0.62	300-400	23.4	5/1/97	No oxidant feed
3	Sludge at 6 wt%	0.6	625	23.4	5/6/97	Workup tests at 6 wt%
4	Sludge at 6 wt%	0.75	610	20.8	5/7/97	
5	Sludge at 6 wt%	0.74	615	13.8	5/7/97	Performed to determine effect of pressure
6	Sludge at 6 wt%	0.66	605	7.72	5/13/97	
7	Sludge at 6 wt%	0.77	505	23.4	5/14/97	
8	Sludge at 6 wt%	0.85	590	23.4	5/9/97	Performed to determine effect of temperature
9	Sludge at 6 wt%	0.85	545	23.4	5/9/97	
10	Sludge at 6 wt%	0.85	595-635	23.4	5/9/97	Performed to determine effect of flow
11	Sludge at 6 wt%	0.76	520	23.4	5/14/97	
12	Sludge at 10 wt%	0.65	580	23.4	5/16/97	Performed to determine pressure and
13	Sludge at 10 wt%	0.67	505	23.4	5/16/97	temperature effects with 10% sludge.
14	Sludge at 10 wt%	0.82	500	2220	5/16/97	
15	Sludge at 10 wt%	0.65	550-610	23.4	5/23/97	Initial heat recovery heat exchanger test.

TABLE 3-2
TEST MATRIX FOR SCWG TESTS

Test No.	Feed Type	Sludge Feed Rate (kg/min)	Reactor Inlet Temp. (°C)	Pressure (MPa)	Test Date	Run Duration (min)	Comments
1a	Sludge at 0.5 wt%	0.62	400	23.4	5/1/97	60	Performed at very low concentration as a workup trial and to verify no significant solids deposition in preheater piping. No catalyst bed used.
1b	Sludge at 0.5 wt%	0.62	300	23.4	5/1/97	20	See above.
2	Sludge at 6 wt%	0.48	450-475	23.4	5/14/97	48	No catalyst bed used.
3	Sludge at 7.5 wt%	0.46	525	23.4	7/17/97	84	Coconut shell carbon catalyst bed used.
4	Sludge at 4.1 wt%	0.48	640-660	23.4	11/24/97	109	Coconut shell carbon catalyst bed used.

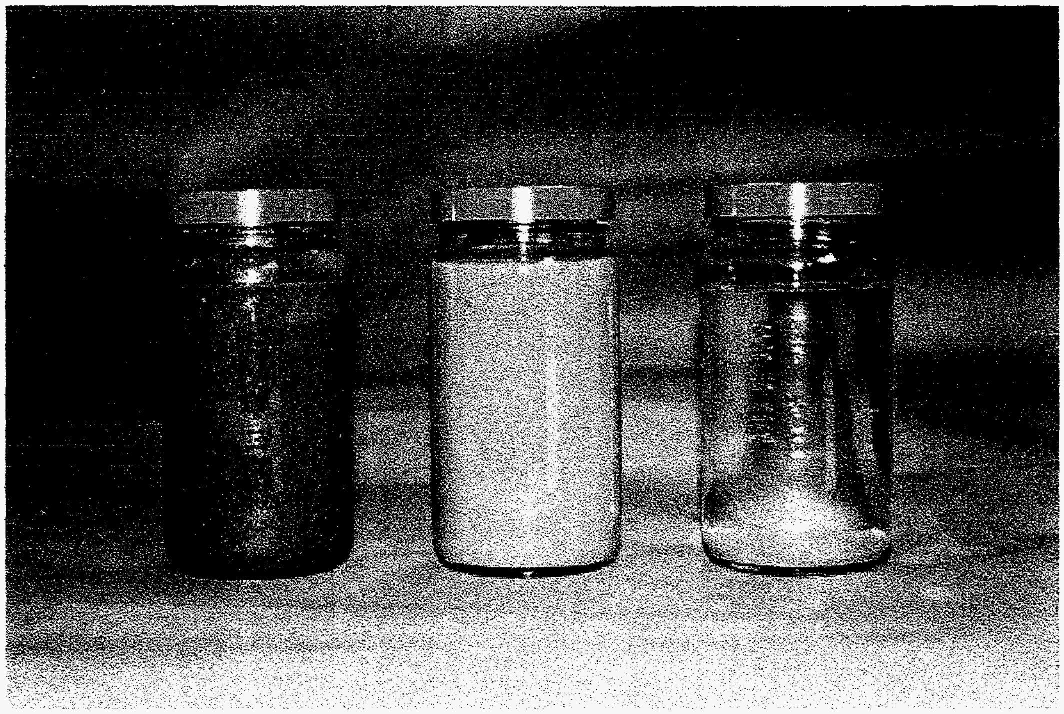


Fig. 3-1. Biosolids feed and SCWO effluent

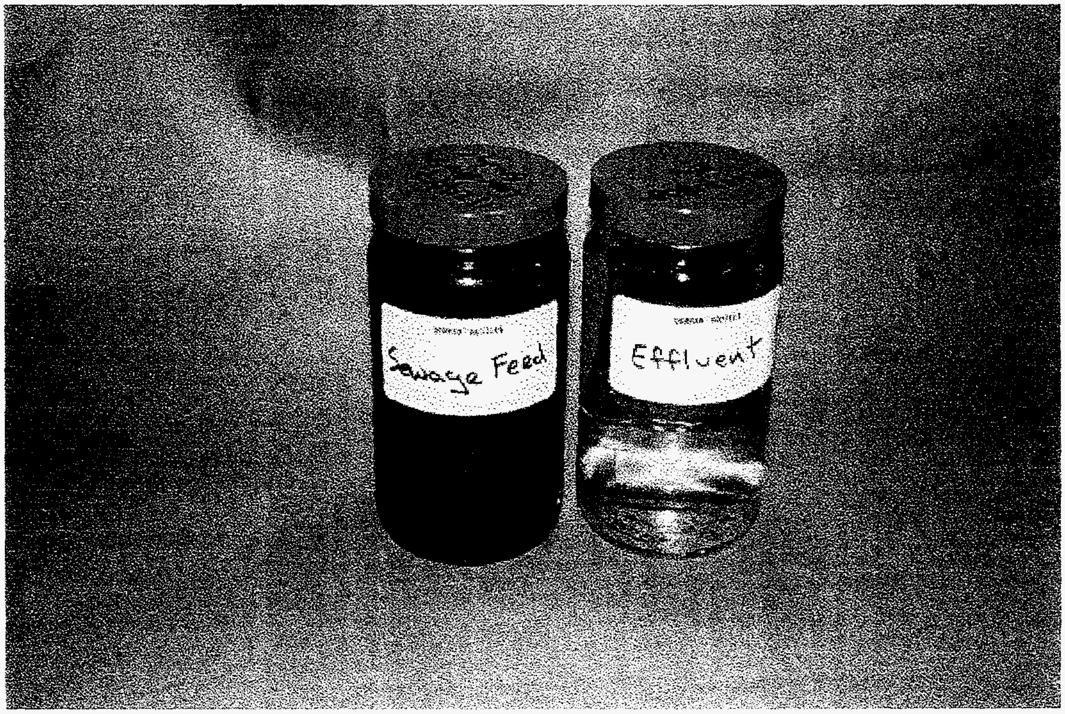


Fig. 3-2. Biosolids feed and SCWG effluent

TABLE 3-3
MINIMUM, MEAN, AND MAXIMUM VALUES OF SEWAGE SLUDGE FEED PARAMETERS

	Primary Sludge			Secondary Sludge		
Parameter	Minimum	Mean	Maximum	Minimum	Mean	Maximum
TOC (ppm)	14,000	21,350	33,500	5300	12,320	16,000
TS (ppm)	49,700	85,790	152,000	20,000	39,910	64,800
TSS (ppm)	48,800	77,178	135,000	24,000	33,344	61,300
VTS (ppm)	10,300	64,760	131,000	3920	31,442	59,200
VSS (ppm)	32,000	63,727	113,000	20,400	27,989	51,100
As (ppm)	5.0	5.2	5.3	5.0	6.9	18.8
Cd (ppm)	0.4	0.74	1.1	0.4	0.94	1.3
Cr (ppm)	1.3	3.1	7.9	1.0	1.5	1.9
Cu (ppm)	9.5	16.7	38.5	5.4	9.1	15.8
Fe (ppm)	194	415	575	75.8	117.8	158
Ni (ppm)	1.0	1.1	1.1	-	-	-
Pb (ppm)	1.0	4.6	11.3	1.0	4.0	8.6
Hg (ppm)	0.1	0.34	0.5	0.1	0.35	0.5
Mo (ppm)	0.8	1.4	5.0	0.8	2.3	12.0
Se (ppm)	5.0	6.4	7.5	5.0	6.6	7.5
Zn (ppm)	34.1	60.1	95.1	18.6	27.2	38.5

Total carbon, hydrogen, and nitrogen content and heating values were also measured for two mixtures of ~10 wt% macerated mixture of 50% primary and 50% secondary sludge. Average concentrations (on a dry basis) were 43.75% carbon, 6.46% hydrogen, and 3.86% nitrogen. The average heating value (on a wet basis) was 1.90 MJ/kg (820 Btu/lb). Concentrations of sludge in the 50/50 mixture were also calculated for five feeds batches: May 14 - 7.4%; May 16 - 10.7%; May 23 - 4.6%; June 5 - 9.1%; and June 9 - 8.8%. Dioxin/furan levels of 10.2 picograms/gram (pg/g) were also measured.

3.2. SIZE REDUCTION AND PUMPING OF SEWAGE SLUDGE

A key objective of the test program was to verify that concentrated sewage sludge could be reliably pumped to the reactor for treatment. Following shakedown of equipment during simulant testing, sewage sludge was successfully pumped under all design conditions.

Sewage sludge pumping tests were performed to demonstrate that GA's proprietary pumping system could be used to pump sludge concentrations up to approximately 10 wt%. Testing involved two primary process steps: feed particle size reduction (performed as a feed pretreatment) and pumping.

Prior experience with pumping solids-containing streams indicated that the as-received sewage sludge would require size-reduction/maceration prior to use in the pilot plant. Several different size-reduction options were evaluated with simulated sludge (a mixture of breakfast cereal, seeds, and paper). An existing GA Gorator® macerator/pump combination, operating in a continuous recycle mode, was found to be the most effective of the size-reduction options tested and was, therefore, used throughout the test program (see Fig. 3-3). The Gorator® macerator was capable of producing particle sizes of <0.5 mm with sewage sludge concentrations up to ~10 wt%. At higher concentrations, plugging at the grinder entrance occurred. Plugging is less likely to occur in larger, commercial-scale grinders designed specifically for sewage sludge size reduction.

Upon receipt of sewage sludge from the Encina plant, the primary and secondary fractions were combined on an equal weight basis and mixed. If 4 to 6 wt% sludge was required for testing, the material was immediately size-reduced in the macerator. Macerator processing times were generally 15 to 30 minutes. If thickened sludge (~10 wt%) was required for testing, the mixed sludge was first treated with a polymer thickening agent which agglomerated the solids fraction and allowed water to be removed via draining through a filter (see Fig. 3.4). The thickened sludge was then processed through the Gorator® macerator. Once adequately size-reduced, the sludge was pumped into a barrel and then stored in a refrigerator until needed. (Note: a continuous process for size-reduction of sewage sludge is more appropriate for a commercial SCWG facility rather than the batch processing employed during pilot plant testing.)

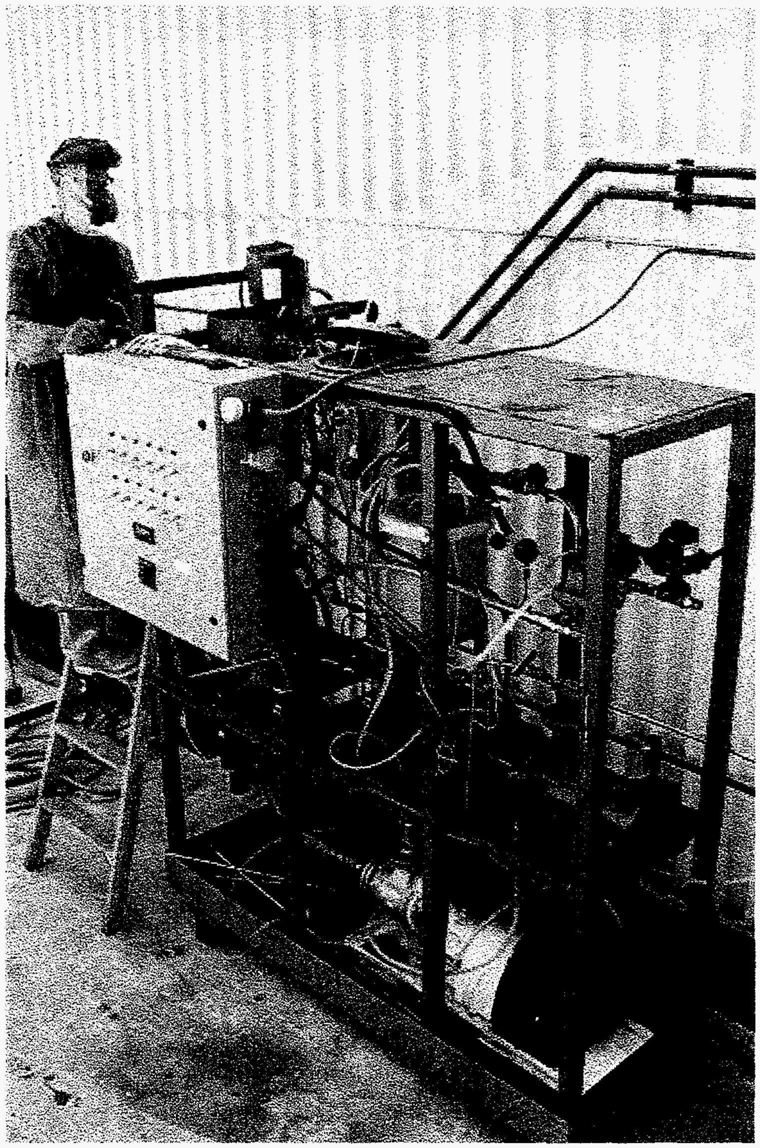
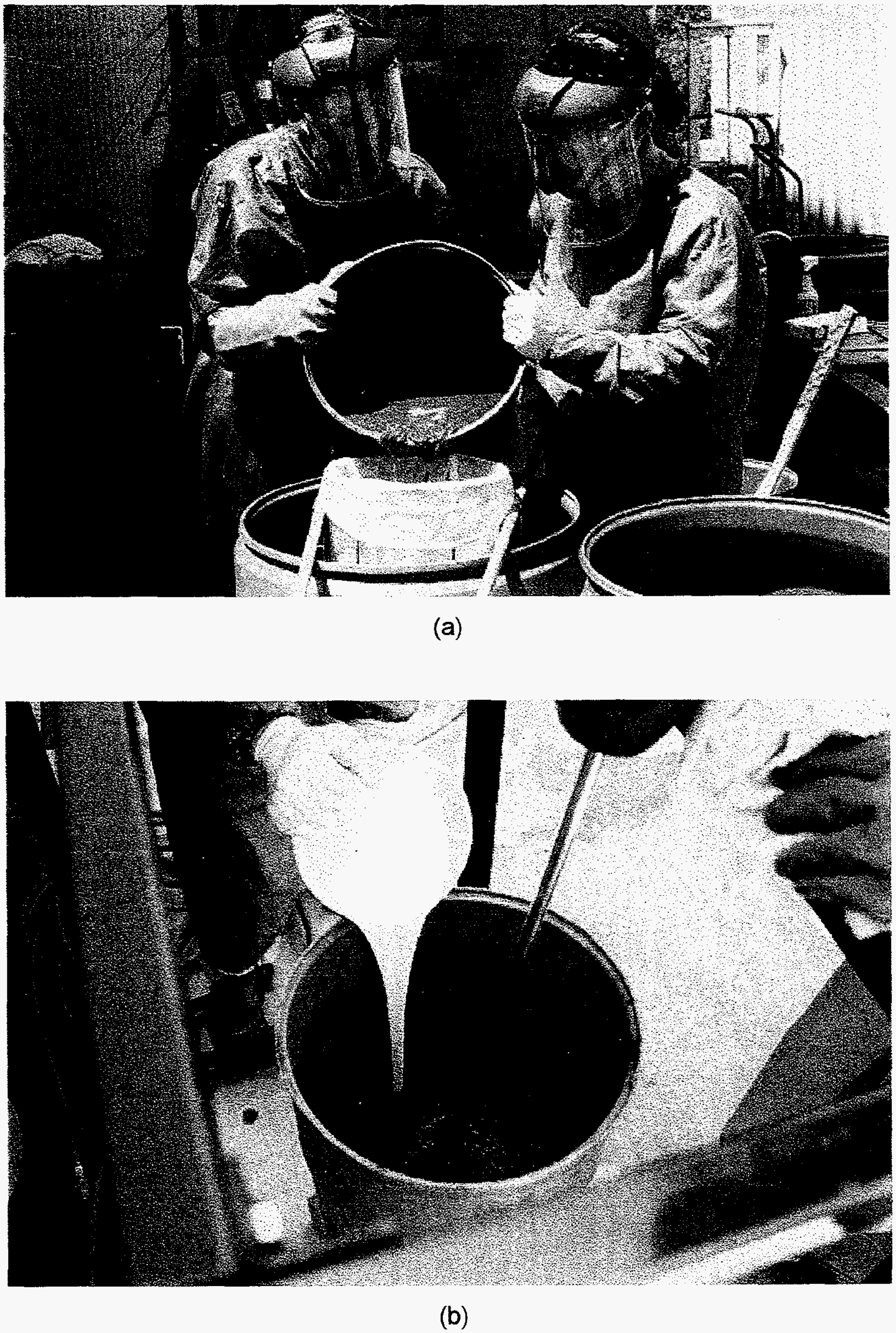


Fig. 3.3. Gorator® macerator and pump



(a)

(b)

Fig. 3.4. Biosolids filtering (a) and thickening (b)

The GA proprietary sewage sludge pumping system was demonstrated to be very effective in pumping sludge with solids contents to up 10.7 wt%. No additive to the feed was required to facilitate pumping. The system was first tested with a simulant in manual mode. After confirming that sewage sludge could be successfully pumped at the desired feed rates (up to ~1 kg/min), pump operations were fully automated and integrated into the pilot plant process control system. During subsequent testing, the pump was found to operate with a high degree of reliability, with little or no evidence of plugging or degradation. This same pump configuration can be utilized for a commercial-scale operation, although more long-term operational data are required to establish pump reliability.

3.3. TEST DESCRIPTION

All testing was performed in the GA pilot plant. Figure 3-5 shows a photograph of the pilot plant reactor/gasifier skid, and Fig. 3-6 shows a simplified process flow diagram. Use of the pilot plant for gasification testing imposed several limitations on test conditions. For example, electrical preheat of the feed to >600°C prior to entering the reactor limited the maximum sewage sludge feed rate due to heater power limits, and reactor wall materials limited maximum reactor operating temperatures. A carbon catalyst bed height of about 1/3 of the available reactor length was chosen to minimize abrasion of the top of the bed due to the feed injection methods employed. Therefore, the test conditions chosen for use during the final optimized test of 11/24/97 were:

Catalyst bed weight:	2.0 kg (~19 in. depth)
Pressure:	23.4 MPa (3400 psig)
Temperature:	600-650°C
Sewage sludge feed rate:	0.45-0.50 kg/min
Test duration:	>1 hr

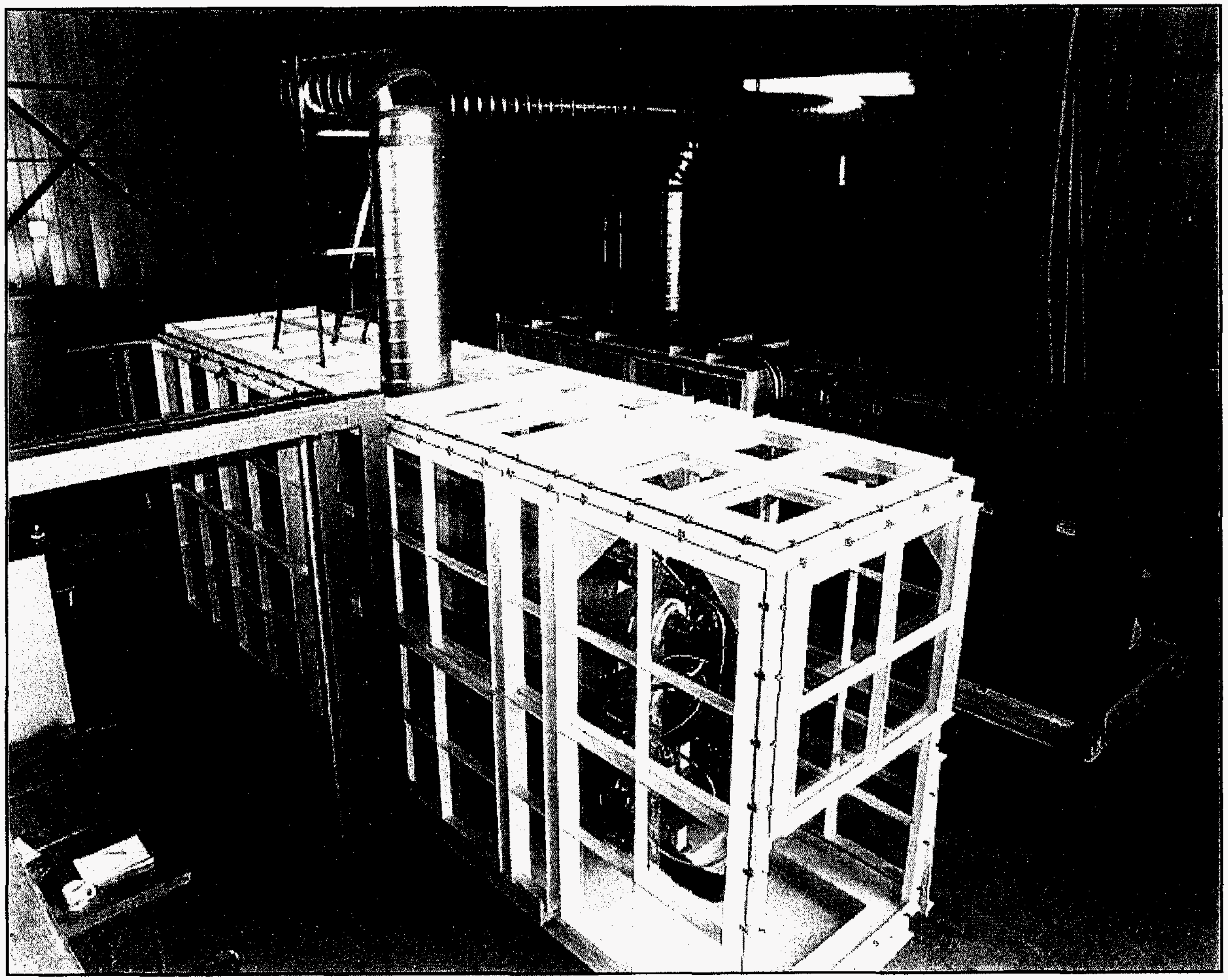


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Fig. 3-5. GA SCW PILOT PLANT REACTOR SKID

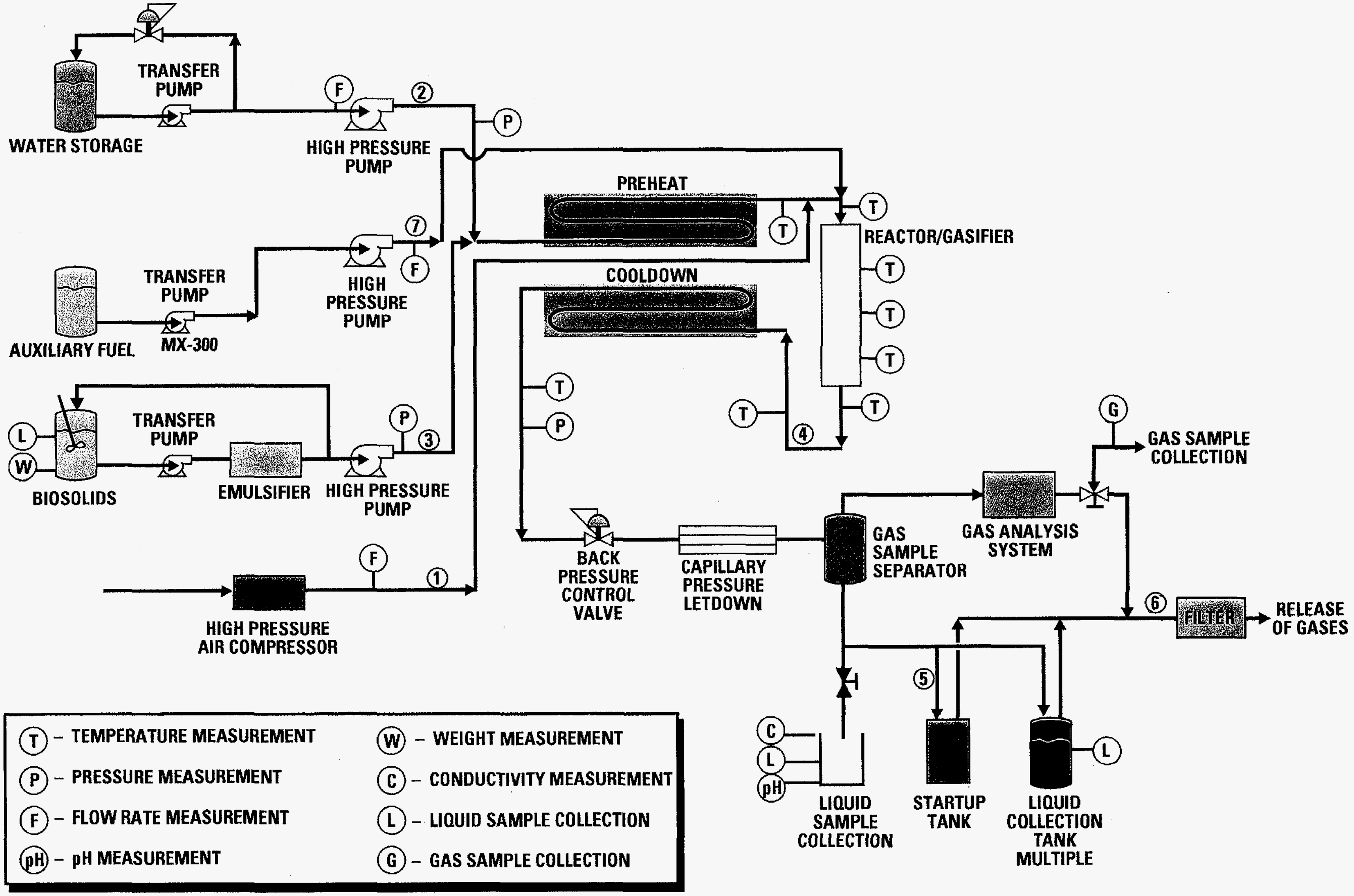

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FIG. 3-6. PROCESS FLOW DIAGRAM FOR BIOSOLIDS SCWO/SCWG TESTS

The following is a simplified description of the procedures involved in performing the SCWG test of 11/24 /97. Procedures for a SCWO test will not be described herein.

1. **Prepare reactor.** Preparations included insertion of coconut carbon catalyst and mesh screen support into the reactor and addition of tape heaters along the reactor external surface.
2. **Heat reactor.** Following equilibration at the target pressure (23.4 MPa), reactor heatup was accomplished via a combination of preheat of reactor feed water and control of external tape heater power level. The water flow rate during heatup was 0.45-0.5 kg/min, and the reactor internal and external temperatures were 600-650°C.
3. **Begin feed of sewage sludge**. Sewage sludge feed from the GA proprietary pumping system was begun at a low flow rate. The flow rate of startup feed water was slowly reduced as the sewage sludge feed rate was increased, such that the system temperature remained relatively constant. This continued until an undiluted sewage sludge feed rate of 0.48 kg/min was attained.
4. **Maintain Conditions**. Temperature, pressure, and sewage sludge flow rate were maintained at target conditions of 600-650°C, 23.4 MPa, and 0.48 kg/min, respectively. Sewage sludge feed continued for approximately 1.25 hr.
5. **Collect Samples**. Liquid and gaseous effluent samples were collected every 5 to 10 min during sewage sludge feed. Liquid samples were collected in 250-ml glass bottles, and gas samples were collected in 3-l sample bags.
6. **Shut Down System.** Sewage sludge feed was terminated, and water flow was initiated. Reactor tape heaters were turned off.

Figure 3-7 presents a plot of the reactor internal and wall temperatures observed during the SCWG test of 11/24/97. The internal temperature at 40 in. was located just above the top of the carbon catalyst bed. The reactor pressure is also included. To aid in review of the plot, sewage sludge feed began at 1723 hours, reached full flow of 0.48 kg/min at 1756 hours, and ended at 1912 hours.

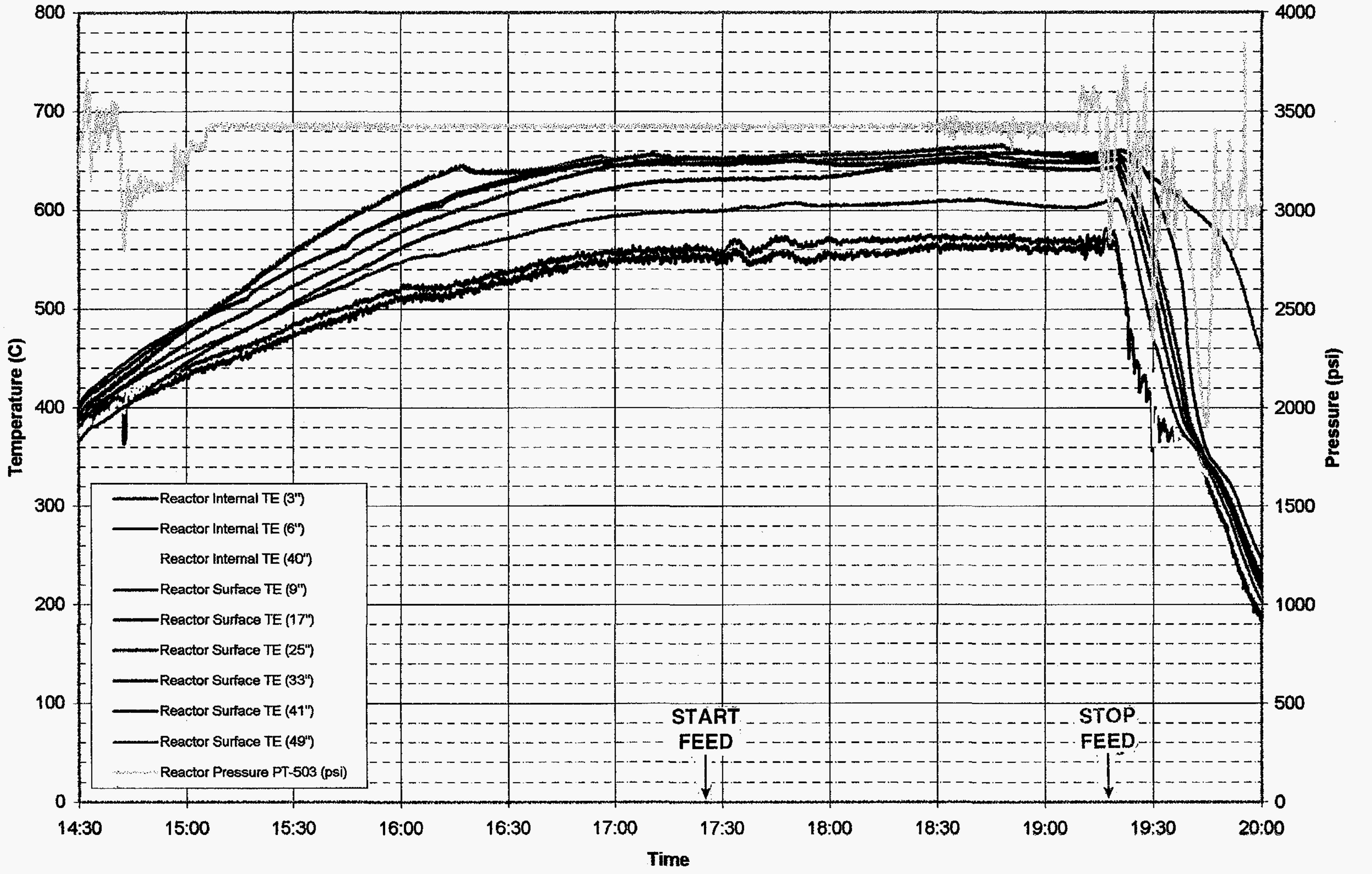

Fig. 3-7. REACTOR TEMPERATURE PROFILE FOR SCWG RUN OF 11/24/97

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3.4. ANALYTICAL RESULTS

During pilot plant testing, liquid and gaseous effluent samples are routinely collected for later analysis. Typical liquid analyses may include TOC, solids or ash content, anions, metals, and pH, while gas analyses will typically include component concentrations such as CO or CH_4. For the SCWG tests included in Table 3-2, liquid analyses were limited to TOC. More detailed analyses were performed on the gas samples, including analysis for H_2, CH_4, CO, CO_2, O_2, N_2, and a host of higher molecular weight hydrocarbons. Not all analyses were performed for all tests. The results of the liquid and gas sample analyses are presented below in Tables 3-4 and 3-5.

Typical sewage sludge feeds contain a small percentage of nonoxidizable or nongasifiable solids such as metal oxides or sand. For the gasification test of 11/24, for example, the ash content of the feed was measured at 0.8%. Because of the presence of the carbon catalyst bed, which tended to retain ash solids, no solids were contained in the liquid effluent during this run, at least during the early portion of the run when pressure control was optimum (see Section 3.6). Therefore no characterization of solids formed during the SCWG treatment of sewage sludge was attempted. For general comparison purposes, however, Fig. 3-8 shows the results of a particle size distribution analysis performed for a solid collected during SCWO treatment of sewage sludge.

Based on TOC analyses for the test of 11/24/97, the organic carbon content in the feed was approximately 2.65%. Assuming an average liquid effluent TOC concentration of 1600 ppm, the gasification efficiency for carbon (to volatile carbon-containing species) was 94%. No hydrogen analysis was performed on the feed for this test. However, assuming a carbon-to-hydrogen weight ratio in the feed of 6.7 to 1 (typical of prior analyses), the hydrogen gasification efficiency (for H_2 formation only) was estimated at 28.5%. These analyses neglect potential organic material holdup in the bed. However, based on post-test analysis, holdup was small.

3.5. HEAT RECOVERY

The hot reactor effluent from SCWO and SCWG processes can be used for heat recovery in two different ways. The energy can be used to preheat the feed material, thereby reducing electrical or gas-fired heater requirements, or the energy can be used for driving external processes such as turning a turbine for electricity generation. During pilot plant testing, only the use of heat recovery for feed preheat was utilized.

TABLE 3-4
LIQUID EFFLUENT ANALYSIS RESULTS

Test No.	Test Date	Sample No.	Sample Time	TOC (ppm)
1a	5/1/97	None	---	---
2	5/14/97	E31	1705	530
"	"	E34	1720	7960
3	7/17/97	E2	1345	589
"	"	E4	1418	786
"	"	E6	1438	746
4	11/24/97	Feed	---	26500
"	"	E2	1749	608
"	"	E3	1802	1160
"	"	E5	1815	1340
"	"	E6	1824	1560
"	"	E7	1829	1510
"	"	E9	1838	1570
"	"	E11	1854	1740

For low heating value feeds, such as sewage sludge, heat recovery is important. In order to maintain adequate reactor temperature to ensure full oxidation or gasification, heat input is required through feed preheat, auxiliary fuel addition, or a combination of both. The degree of feed preheat that can be used, at least for oxidation conditions, may be limited by pyrolysis. If the temperature of the sewage sludge feed reaches ~400°C, in the absence of oxygen, char formation may result, and char is difficult to fully oxidize. Under gasification conditions, heating to 600-650°C will undoubtedly produce some char, although the char produced presents more of a potential plugging problem than an inherent limitation on hydrogen production.

TABLE 3-5
GASEOUS EFFLUENT ANALYSIS RESULTS

Test No.	Test Date	Sample No.	Sample Time	H_2 (vol %)	CH_4 (vol %)	Non-CH_4HCs (vol %)	CO (vol %)	CO_2 (vol %)	O_2(a) (vol %)	N_2 (vol %)
1a	5/1/97	G1	1245	0.35	0.06	~0.25(b)	1.1	11	19	N/A(c)
2	5/14/97	G4	1648	0.04	0.003	N/A	0.004	1.2	16	N/A
"	"	G5	1655	0.2	0.04	N/A	0.06	0.68	13	N/A
"	"	G6	1703	1.3	0.89	N/A	1.1	4.5	10	N/A
"	"	G7	1721	3.3	3.08	N/A	2.5	7.4	13	N/A
3	7/17/97	G3	1433	18	21	>18.0(4d	22	19	0.2	1
"	"	G4	1452	17	20	>18.6(d)	22	21	0.1	0.4
4	11/24/97	G2	1759	24.3	23.1	5.6(e)	7.85	22.0	1.06	16.2
"	"	G4	1820	25.3	28.5	8.4(e)	10.3	24.4	0.51	2.70
"	"	G6	1840	24.5	28.4	8.9(e)	10.9	24.2	0.60	2.47

(a) The presence of significant oxygen concentrations in the gaseous effluent indicates a system leak whereby air is contaminating the sample. Measured concentrations above must be adjusted to compensate for dilution. (b) Sum of measured concentrations of multiple volatile organics (e.g., butane, butene, pentadiene, etc.).

(c) N/A = not available, analysis not performed.

(d) Sum of multiple volatile organics. Actual value slightly greater due to several volatile species beyond calibrated concentration.

(e) Sum of multiple volatile organics.

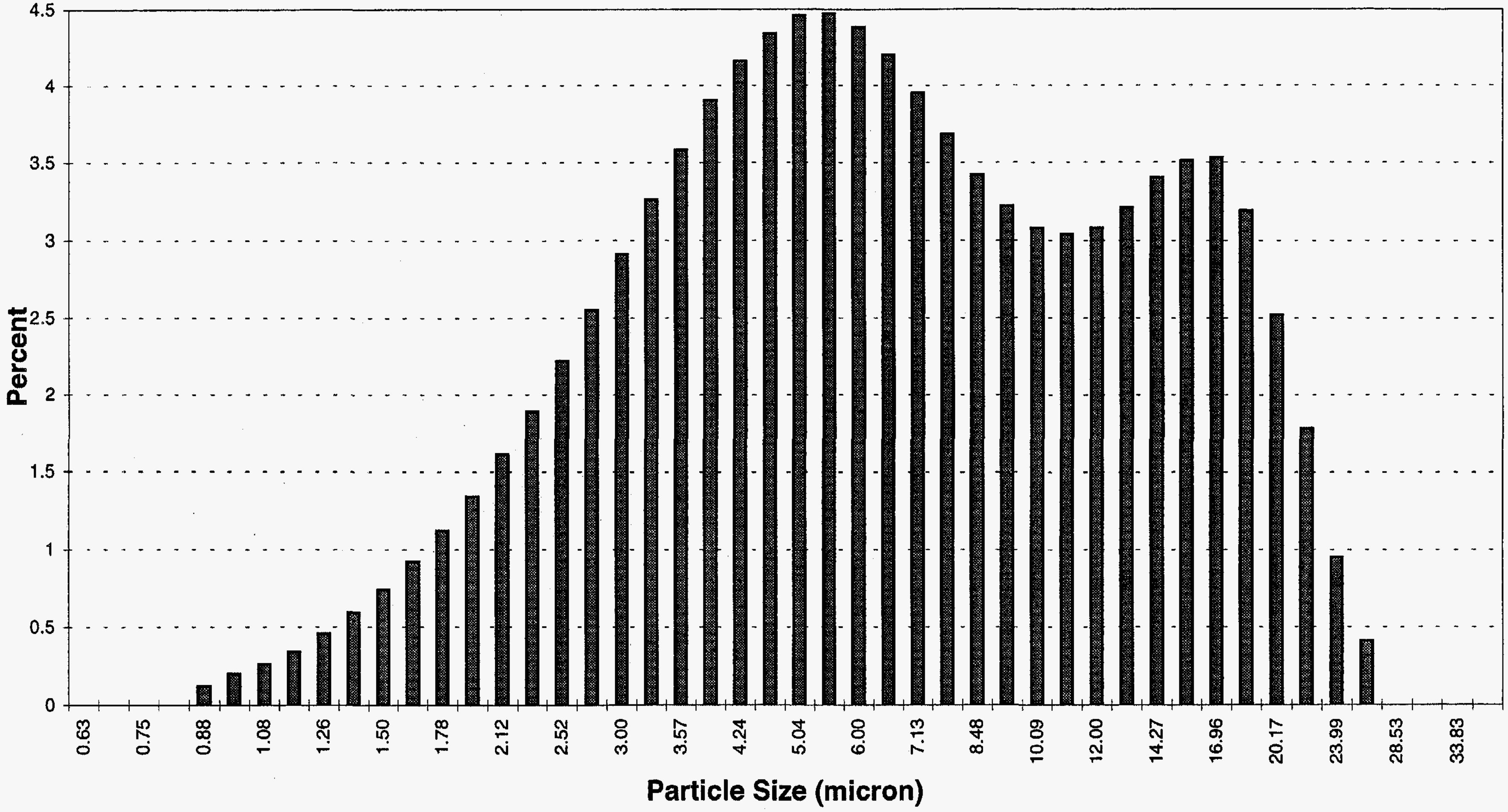

FIG. 3-8. SOLID EFFLUENT PARTICLE SIZE DISTRIBUTION FOR SCWO OF BIOSOLIDS

During SCWO workup testing, the feasibility of utilizing heat recovery was tested in three different ways: (1) simulated heat recovery using electrical preheat, (2) actual heat recovery heat exchange in combination with low level electrical preheat, and (3) actual heat recovery heat exchange alone. During tests utilizing electrical preheat, the preheater outlet control temperature was 300-400°C. Some solids accumulation in the preheater was observed, especially at lower flow rates. When the heat recovery heat exchanger was on line, exchanger outlet temperatures of 330-380°C were used. No signs of solids accumulation within the heat recovery heat exchanger were observed, probably due to the significantly higher velocities employed in the heat recovery heat exchanger relative to the preheater. Since the preheat temperature in all three cases was $\leq$400°C, the use of auxiliary fuel was required in order to achieve the desired reactor operating temperature of 550-650°C.

For SCWG processes, some degree of char formation is probably unavoidable. However, as long as overall char production is reasonably low and it does not present a plugging problem downstream, higher heat recovery temperatures can be used, lessening the need for external preheat.

3.6. PRESSURE EFFECTS

The coconut carbon catalyst chosen for use was quite friable. Thus, during both pilot plant tests utilizing the carbon catalyst bed, bed attrition was a problem. For example, during the test of 11/24/97, pressure control was excellent for about the first 70 minutes of sewage sludge feed (of ~110 minutes total sewage sludge feed time). Over this time, the liquid effluent samples were clear. Then, small bed particles began to pass through the bed support and collect in the downstream pressure control valve, thus worsening pressure control. With worse pressure control, the pressure fluctuations in the reactor began to increase, resulting in buffeting of the bed. This buffeting led to even more rapid bed attrition and even worse pressure control, eventually necessitating test termination. Clearly, bed attrition must be reduced for a commercial-scale SCWG process. Bed attrition can be reduced in several ways, including: (1) more robust catalyst materials, (2) improved pressure control methods to reduce reactor pressure fluctuations, (3) lower throughputs to reduce velocities through the bed, and (4) higher operating pressures to increase process fluid densities, thereby also reducing velocities through the bed. Additional testing is needed to identify the best method or methods for commercial-scale application.

3.7. TEMPERATURE EFFECTS

For typical SCWO homogeneous gas phase kinetics, the reaction rate for organic destruction is temperature dependent according to the Arrhenius equation. Relatively small increases in temperature will, therefore, yield relatively large increases in organic destruction. The kinetics effects are reasonably well understood and will not be discussed herein. To determine the temperature effects for SCWG applications, temperatures ranging from 300°C to 660°C were investigated as shown in Table 3-2. Unfortunately, for the early low-temperature tests of 5/1/97 and 5/14/97, no carbon catalyst bed was used, so the temperature effects are obscured by the catalytic effects of the bed. Therefore, the best runs for determination of the qualitative effects of temperature on hydrogen production are the runs of 7/17/97 and 11/24/97. Both runs utilized a 2.0 kg carbon catalyst bed (~19 in. deep within the reactor) with a similar sludge flow rate. Aside from temperature, the only other significant difference between the runs was the solids concentration of the feed, 7.5 wt% for the run of 7/17/97 and 4.1 wt% for the run of 11/24/97.

The Run of 7/17 97 was performed at a maximum reactor temperature of approximately 540°C. Based on reactor wall temperature data, the carbon catalyst bed temperature reached only about 525°C. The target temperature of ~600°C could not be achieved due to excessive heat loss from the reactor. The heat tapes added to the reactor wall to counteract heat loss had insufficient heating capability. For the test of 11/24/97, the reactor insulation and external reactor heat tape power were improved significantly such that the reactor and carbon catalyst bed could be uniformly maintained at ~650°C. At a catalyst bed temperature of ~525°C, gaseous effluent analyses show a hydrogen concentration of approximately 18 vol %, with methane and other higher molecular weight hydrocarbons totaling almost 40 vol %. At a catalyst bed temperature of ~650°C, the hydrogen concentration increases to about 25 vol %, while the methane/hydrocarbon concentration decreases only slightly. The major difference appears to be in the relative CO concentrations. One possible explanation is that at higher temperatures some steam reforming of the higher molecular weight hydrocarbons to form CO and hydrogen is taking place (1), while some of the CO is then being converted to CO_2 and hydrogen via the water-gas shift reaction (2). While some improvement in hydrogen production was realized by increasing the operating temperature from 525°C to 650°C, the improvement was only moderate, and the hydrogen concentration still falls somewhat below the laboratory-scale test value of 33 vol % (Ref. 1).

$$(1)\ C_nH_m + nH_2O + \text{heat} \rightarrow nCO + (m/2 + n)H_2$$

$$(2)\ CO + H_2O \rightarrow CO_2 + H_2 + \text{heat}$$

The liquid effluent TOC values were shown previously in Table 3-4 for the gasification runs of 7/17/97 and 11/24/97. The TOC values for the ~650°C run of 11/24/97 were significantly higher than those measured for the ~525°C run of 7/17/97. Generally, at least under oxidizing conditions, the TOC value is expected to decrease rapidly with an increase in temperature. One possible explanation for this could be if the above steam reforming and water gas-shift reactions are the rate limiting steps in hydrogen production from sewage sludge. At higher operating temperature, the pyrolysis of sewage sludge and the production of soluble organic species may be increased, and this increase will yield a comparable increase in the liquid phase TOC level unless the organics are themselves consumed by the steam reforming and water gas-shift reaction pathways. For the test of 11/24/97, the TOC concentration of the sewage sludge feed was 26,500 ppm. The effluent samples were generally about 1600 ppm, which yields a TOC destruction/conversion of 94%, neglecting any organic-containing solids which may have collected on the carbon catalyst bed.

3.8. PRESSURE LETDOWN

Pressure letdown was accomplished through a combination of pressure control valves and capillaries. The fine pressure control was performed by a single control valve. This valve was intended to take only a portion of the required system pressure drop in order to reduce valve wear. The remainder of the pressure drop was taken over a control valve and a capillary connected in parallel. This arrangement proved to work well for a portion of the testing. As long as bed material was not abraded and passed through the mesh support screen, pressure control was excellent, and the liquid effluent samples were clear. After about 1 hr of sewage sludge feed, however, some solid particles began to appear in the effluent, and pressure control began to degrade. This degradation of control led to some pressure cycling in the reactor which further abraded the bed material, which worsened pressure control. This cycle continued for about another 40 min, after which pressure control was poor enough to necessitate run termination. The solids exiting the reactor were black and appeared to be crushed carbon catalyst bed material. Another possibility is that the solids were char from pyrolysis of the sewage sludge feed which had slowly worked their way down through the catalyst bed. A post-test inspection, however, showed some fine carbon slurry present in the top 1-3 in. of the bed, probably a result of feed char. No signs of a similar carbon slurry were found elsewhere in the bed.

For a full-scale plant design, several system modifications could be made to improve pressure control, including use of more robust catalysts, better catalyst support methods, and larger, more forgiving control valves.

3.9. EFFECTIVENESS OF THE CARBON CATALYST

Laboratory-scale SCWG testing has shown near stoichiometric yields of hydrogen production for tests utilizing a carbon catalyst bed (Ref. 2). During pilot plant testing, tests were conducted both with and without a catalyst bed in an effort to shed further light on the bed effectiveness for gasification. The first two series of tests, as shown previously in Table 3-2, used maximum operating temperatures of only 300-475°C. During these tests, the maximum hydrogen concentration in the effluent was only 3.3 vol % (see Table 3-5). The presence of significant quantities of oxygen imply a system leak, but even accounting for the leak yields a maximum hydrogen concentration of only ~8.7 vol%.

The final two series of pilot plant tests utilized a carbon catalyst bed. The carbon used was a coconut shell carbon, supplied in 4-mm pellets from Barnabey and Sutcliffe. The size of the individual carbon particles was significantly greater than that used during laboratory-scale studies. Approximately 2 kg of carbon catalyst was used for each test. As shown in Table 3-2, these tests used significantly higher reactor temperatures (525°C and ~650°C) than the earlier tests without a catalyst. Very low oxygen concentrations were observed in the gaseous effluent, thus indicating that significant inleakage of air into the effluent samples did not occur. At a bed temperature of 525°C, the maximum hydrogen concentration in the effluent was measured at 18 vol %, about twice that observed at 475°C without a bed. At a reactor temperature of 640-660°C, the hydrogen concentration in the effluent increased to about 25 vol%. The increase in hydrogen concentration in the gaseous effluent showed a dependence on temperature as seen in the test results at 525°C and ~650°C, with higher temperatures appearing to be beneficial. The benefit of using a carbon catalyst bed is not quite as clear. Unfortunately, due to funding limitations, no test was performed at a prototypic temperature (600 to 650°C) without a carbon catalyst bed. Since the early runs performed without a carbon catalyst bed also utilized low temperatures, the temperature effect could not be separated from the bed effect.

3.10. COMPARISON WITH LABORATORY-SCALE DATA

Table 3-6 shows a comparison between the results of the pilot plant SCWG run of 11/24/97 and a laboratory test on sewage sludge (without feed enhancement additives)

(Ref. 1). The results compare relatively well. The laboratory data show somewhat higher hydrogen levels, while the pilot data show higher CO and hydrocarbon concentrations. It thus appears that the steam reformation and water gas-shift reactions discussed in Section 3.7 did not progress to the same extent in the pilot-scale testing as in the laboratory-scale work. More testing is required for process optimization.

TABLE 3-6
COMPARISON BETWEEN PILOT-SCALE AND LABORATORY-SCALE SCWG DATA FOR SEWAGE SLUDGE FEED

Parameter/Component	Pilot Plant Test of 11/24/97[a]	Laboratory-Scale Test
Temperature (°C)	600 to 650	600
Pressure (MPa)	23.4	34.4
WHSV[b] [(g/hr)/g]	0.6	0.5
Liquid TOC (ppm)	~1600	280
H_2 (vol %)	24.9	33
CO (vol %)	10.6	2.9
CO_2 (vol %)	24.3	36
CH_4 (vol %)	28.5	24
C_2 and above (vol %)	8.7	6.78

(a) Gas concentrations given are an average of the G4 and G6 analyses (see Table 3-5).
(b) WHSV = weight hourly space velocity (feed concentration x feed flow rate / amount of catalyst).

3.11. REFERENCES

1. Antal, M., X. Xu, Y. Matsumura, and J. Stenberg, "Hydrogen Production from High-Moisture Content Biomass in Supercritical Water", Proceedings of the 1995 U. S. DOE Hydrogen Program Review, NREL/CP-430-20036, Volume II, pp. 757-795, September 1995.

2. Xu, X., Y. Matsumura, J. Stenberg, and M. Antal, Jr., "Carbon-Catalyzed Gasification of Organic Feedstocks in Supercritical Water", Ind. Eng. Chem. Res., 1996, Vol. 35, pp. 2522-2530.

APPENDIX C
BACKUP FOR SYSTEM COSTING

COSTS FOR 27 MT/DAY SCWG SYSTEM, 20% BIOSOLIDS, HIGHER HYDROGEN YIELDS

PLANT SIZE, T/DAY BIOSOLIDS	30					
PRETREATED BIOLSOLIDS, wt%	20					
CAPITAL COSTS						
Item	**Size**	**Units**	**Size Basis**	**Materials**	**Cost**	**Cost Basis**
Biosolids storage tank	8111	gal	4 hours holdup +25% head space	Concrete	$17,000	Engineering estimate
Biosolids transfer pump	135	gpm	4x progressive cavity pump	SS	$11,000	0.6 exponent scale from 100 MTD SCWO Plant
Emulsifier macerator	135	gpm	4x progressive cavity pump	SS	$23,000	0.6 exponent scale from 100 MTD SCWO Plant
Progressive cavity pump	34	gpm	28 gpm required	SS	$78,000	0.6 exponent scale from 100 MTD SCWO Plant
Filter press	27	MT/day	M&EB	CS	$0	Not required
Liquefier/pump	1146	gal	30 minutes residence time	Ti/steel	$397,000	Estimated from Zimpro vessel
Heat recovery heat exchanger	2.71	MW	M&EB	C276	$810,000	0.6 exponent scale from 100 MT SCWO Plant
Gas-fired heater	3.1	MW	M&EB		$311,000	0.6 exponent scale from 100 MTD SCWO Plant
Flue gas heat exchanger	2.2	MW	M&EB	SS	$156,000	Half of fired heater
Reactor	1187	gal	1.5 minutes residence time	Alloy 718	$617,000	0.6 exponent scale from MODAR vessel x 2/3
Waste heat boiler	1.3	MW	M&EB	C276	$286,000	0.6 exponent scale from 100 MTD SCWO Plant
Gas/Liquid separator	172	gal	5 min liquid RT, 50% head space	SS	$68,000	0.6 exponent scale from 33 gal vessel
Liquid letdown valve	21	gpm	M&EB	TiN/SS	$16,000	Same as 100 MTD SCWO Plant
System pressure control valve	27	gpm	M&EB	SS	$19,000	0.6 exponent scale from liquid letdown valve
Membrane separator	772,010	scfd	M&EB		$200,000	Phone quote
PSA module	772,010	scfd	M&EB		$200,000	Mann report
Hydrogen storage tank			M&EB		$100,000	Engineering judgment.
Total major equipment					$3,309,000	
Bulk items factor					$4,467,000	1.35 times major equipment cost
Design & fab labor factor					$1,985,000	0.6 times major equipment cost
Control system					$80,000	GA SCWO systems
Facilities					$331,000	0.1 times major equipment cost
Startup cost					$662,000	0.2 times major equipment cost
TOTAL INSTALLED COSTS					$10,834,000	
Notes:						
1. Overall factor on major equipment	3.3					
2. All equipment sizing is at least 20% excess capacity over requirement.						
3. Antal high H2 yields assumed.						
OPERATING COST, $/YR @ 330 ANNUAL OPERATING DAYS						
Item	**Assumption**				**Cost**	**Cost Basis**
Labor	4 operators				$150,000	$18.75/hr
Utilities, etc.	1% of capital cost				$108,000	0.5 SCWO utility costs
Hydrogen credit	$10/GJ; 0.1184 GJ (lower)/kg				$ (697,000)	Mann report values
Steam credit	M&EB values				$ (298,000)	Mann report values
Feed credit	$90/bone dry ton				$ (891,000)	0.75 of Encina disposal cost
TOTAL					($1,628,000)	
IRR @ $120/ton avoided disposal cost						
- Initial investment	($10,834,000)					
- Year 1	$1,628,000	-85%				
- Year 2	$1,628,000	-53%				
- Year 3	$1,628,000	-31%				
- Year 4	$1,628,000	-18%				
- Year 5	$1,628,000	-9%				
- Year 6	$1,628,000	-3%				
- Year 7	$1,628,000	1%				
- Year 8	$1,628,000	4%				
- Year 9	$1,628,000	7%				
- Year 10	$1,628,000	8%				

COSTS FOR 27 MT/DAY SCWG SYSTEM, 40% BIOSOLIDS, HIGHER HYDROGEN YIELDS

PLANT SIZE, T/DAY BIOSOLIDS	30					
PRETREATED BIOLSOLIDS, wt%	40					
CAPITAL COSTS						
Item	**Size**	**Units**	**Size Basis**	**Materials**	**Cost**	**Cost Basis**
Biosolids storage tank	4516	gal	4 hours holdup +25% head space	Concrete	$12,000	Engineering estimate
Biosolids transfer pump	75	gpm	4x progressive cavity pump	SS	$8,000	0.6 exponent scale from 100 MTD SCWO Plant
Emulsifier macerator	75	gpm	4x progressive cavity pump	SS	$17,000	0.6 exponent scale from 100 MTD SCWO Plant
Progressive cavity pump	19	gpm	15 gpm required	SS	$54,000	0.6 exponent scale from 100 MTD SCWO Plant
Filter press	27	MT/day	M&EB	CS	$125,000	Vendor quote/engineering judgment
Liquefier/pump	638	gal	30 minutes residence time	Ti/steel	$279,000	Estimated from Zimpro vessel
Heat recovery heat exchanger	0.52	MW	M&EB	C276	$104,000	0.6 exponent scale from 10 MTD SCWO Plant
Gas-fired heater	3.1	MW	M&EB		$311,000	0.6 exponent scale from 100 MTD SCWO Plant
Flue gas heat exchanger	2.2	MW	M&EB	SS	$156,000	Half of fired heater
Reactor	621	gal	1.5 minutes residence time	Alloy 718	$418,000	0.6 exponent scale from MODAR vessel x 2/3
Waste heat boiler	0.8	MW	M&EB	C276	$85,000	0.6 exponent scale from 10 MTD SCWO Plant
Gas/Liquid separator	47	gal	5 min liquid RT, 50% head space	SS	$31,000	0.6 exponent scale from 33 gal vessel
Liquid letdown valve	6	gpm	M&EB	TiN/SS	$16,000	Same as 100 MTD SCWO Plant
System pressure control valve	30	gpm	M&EB	SS	$42,000	0.6 exponent scale from liquid letdown valve
Membrane separator	772,010	scfd	M&EB		$200,000	Phone quote
PSA module	772,010	scfd	M&EB		$200,000	Mann report
Hydrogen storage tank			M&EB		$100,000	Engineering judgment.
Total major equipment					$2,158,000	
Bulk items factor					$2,913,000	1.35 times major equipment cost
Design & fab labor factor					$1,295,000	0.6 times major equipment cost
Control system					$80,000	GA SCWO systems
Facilities					$216,000	0.1 times major equipment cost
Startup cost					$432,000	0.2 times major equipment cost
TOTAL INSTALLED COSTS					$7,094,000	
Notes:						
1. Overall factor on major equipment	3.3					
2. All equipment sizing is at least 20% excess capacity over requirement.						
3. Antal high H2 yields assumed.						
OPERATING COST, $/YR @ 330 ANNUAL OPERATING DAYS						
Item	**Assumption**				**Cost**	**Cost Basis**
Labor	4 operators				$150,000	$18.75/hr
Utilities, etc.	1% of capital cost				$71,000	0.5 SCWO utility costs
Hydrogen credit	*$10/GJ; 0.1184 GJ (lower)/kg*				$ (697,000)	*Mann report values*
Steam credit	M&EB values				$ (298,000)	Mann report values
Feed credit	$90/bone dry ton				$ (891,000)	0.75 of Encina disposal cost
TOTAL					($1,665,000)	
IRR @ $120/ton avoided disposal cost						
- Initial investment	($7,094,000)					
- Year 1	$1,665,000	-77%				
- Year 2	$1,665,000	-38%				
- Year 3	$1,665,000	-16%				
- Year 4	$1,665,000	-2%				
- Year 5	$1,665,000	6%				
- Year 6	$1,665,000	11%				
- Year 7	$1,665,000	14%				
- Year 8	$1,665,000	17%				
- Year 9	$1,665,000	18%				
- Year 10	$1,665,000	20%				

ANALYSIS OF BCL COST ESTIMATES BY M. MANN

Line No.	30 tpd	Scheme 2					Closest Mann	
	Equipment				SCWG 40% Costs		Categories	
1	Uninstalled capital	$572,940			Total major equipment	$2,158,000	$572,940	line 1
2	Other equipment	$521,042	91%	of line 1	Bulk items + control system	$2,993,000	$1,560,325	lines 2+6+7+8
3	Total equipment	$1,093,982			Design & fab labor	$1,295,000	$1,323,719	lines 4+13
4	Installation cost	$514,172	47%	of line 3	Facilities	$216,000	$1,137,741	lines 9+10+11+12
5	Total installed cost	$1,608,154		line 3 + line 4	Startup cost	$432,000	$459,472	line 14?
					TOTAL INSTALLED COSTS	$7,094,000	$5,054,197	line 16
	Other fixed capital							
6	Instrumentation	$196,917	18%	of line 3				
7	Piping	$722,028	66%	of line 3				
8	Electrical	$120,338	11%	of line 3				
9	Buildings	$196,917	18%	of line 3				
10	Yard improvements	$109,398	10%	of line 3				
11	Service facilities	$765,787	70%	of line 3				
12	Land	$65,639	6%	of line 3				
13	Engineering and construction	$809,547	74%	of line 3				
14	Contingencies	$459,472	42%	of line 3				
15	Total	$3,446,043						
16	**Total Fixed Capital Investment**	$5,054,197		line 5 + line 15				
	Overall Factor on Equipment	3.14		line 16/line 5				
	Burlington Gasifier							
	200	tpd						
	$375	per kWe						
	Scale down to 30 tpd							
	$1,171	per kWe						
	40%	electrical efficiency						
	$468	per kW fuel value						
	8500	Btu/lb biomass heating value						
	60,000	lb biomass/day						
	21,250,000	Btu/hr						
	6226	kW						
	$2,915,164	Installed capital cost of gasifier alone						
	$615,339	M. Mann installed cost of gasifier alone						

GENERAL ATOMICS

COSTS FOR 27 MT/DAY SCWG SYSTEM, 20% BIOSOLIDS, LOWER HYDROGEN YIELD

PLANT SIZE, T/DAY BIOSOLIDS	**30**					
PRETREATED BIOLSOLIDS, wt%	**20**					
CAPITAL COSTS						
Item	**Size**	**Units**	**Size Basis**	**Materials**	**Cost**	**Cost Basis**
Biosolids storage tank	8111	gal	4 hours holdup +25% head space	Concrete	$17,000	Engineering estimate
Biosolids transfer pump	135	gpm	4x progressive cavity pump	SS	$11,000	0.6 exponent scale from 100 MTD SCWO Plant
Emulsifier macerator	135	gpm	4x progressive cavity pump	SS	$23,000	0.6 exponent scale from 100 MTD SCWO Plant
Progressive cavity pump	34	gpm	28 gpm required	SS	$78,000	0.6 exponent scale from 100 MTD SCWO Plant
Filter press	27	MT/day	M&EB	CS	$0	Not required
Liquefier/pump	1146	gal	30 minutes residence time	Ti/steel	$397,000	Estimated from Zimpro vessel
Heat recovery heat exchanger	2.72	MW	M&EB	C276	$811,000	0.6 exponent scale from 100 MT SCWO Plant
Gas-fired heater	3.1	MW	M&EB		$310,000	0.6 exponent scale from 100 MTD SCWO Plant
Flue gas heat exchanger	2.2	MW	M&EB	SS	$155,000	Half of fired heater
Reactor	1187	gal	1.5 minutes residence time	Alloy 718	$617,000	0.6 exponent scale from MODAR vessel x 2/3
Waste heat boiler	1.3	MW	M&EB	C276	$286,000	0.6 exponent scale from 100 MTD SCWO Plant
Gas/Liquid separator	172	gal	5 min liquid RT, 50% head space	SS	$68,000	0.6 exponent scale from 33 gal vessel
Liquid letdown valve	21	gpm	M&EB	TiN/SS	$16,000	Same as 100 MTD SCWO Plant
System pressure control valve	27	gpm	M&EB	SS	$19,000	0.6 exponent scale from liquid letdown valve
Membrane separator	411,179	scfd	M&EB		$200,000	Phone quote
PSA module	411,179	scfd	M&EB		$200,000	Mann report
Hydrogen storage tank			M&EB		$100,000	Engineering judgment.
Total major equipment					$3,308,000	
Bulk items factor					$4,466,000	1.35 times major equipment cost
Design & fab labor factor					$1,985,000	0.6 times major equipment cost
Control system					$80,000	GA SCWO systems
Facilities					$331,000	0.1 times major equipment cost
Startup cost					$662,000	0.2 times major equipment cost
TOTAL INSTALLED COSTS					$10,832,000	
Notes:						
1. Overall factor on major equipment	3.3					
2. All equipment sizing is at least 20% excess capacity over requirement.						
3. Antal high H2 yields assumed.						
OPERATING COST, $/YR @ 330 ANNUAL OPERATING DAYS						
Item	**Assumption**				**Cost**	**Cost Basis**
Labor	4 operators				$150,000	$18.75/hr
Utilities, etc.	1% of capital cost				$108,000	0.5 SCWO utility costs
Hydrogen credit	$10/GJ; 0.1184 GJ (lower)/kg				$ (371,000)	Mann report values
Steam credit	M&EB values				$ (337,000)	Mann report values
Feed credit	$90/bone dry ton				$ (891,000)	0.75 of Encina disposal cost
TOTAL					($1,341,000)	
IRR @ $120/ton avoided disposal cost						
- Initial investment	($10,832,000)					
- Year 1	$1,341,000	-88%				
- Year 2	$1,341,000	-58%				
- Year 3	$1,341,000	-37%				
- Year 4	$1,341,000	-23%				
- Year 5	$1,341,000	-14%				
- Year 6	$1,341,000	-8%				
- Year 7	$1,341,000	-3%				
- Year 8	$1,341,000	0%				
- Year 9	$1,341,000	2%				
- Year 10	$1,341,000	4%				

COSTS FOR 27 MT/DAY SCWG SYSTEM, 40% BIOSOLIDS, LOWER HYDROGEN YIELDS

PLANT SIZE, T/DAY BIOSOLIDS	**30**					
PRETREATED BIOLSOLIDS, wt%	**40**					
CAPITAL COSTS						
Item	**Size**	**Units**	**Size Basis**	**Materials**	**Cost**	**Cost Basis**
Biosolids storage tank	4516	gal	4 hours holdup +25% head space	Concrete	$12,000	Engineering estimate
Biosolids transfer pump	75	gpm	4x progressive cavity pump	SS	$8,000	0.6 exponent scale from 100 MTD SCWO Plant
Emulsifier macerator	75	gpm	4x progressive cavity pump	SS	$17,000	0.6 exponent scale from 100 MTD SCWO Plant
Progressive cavity pump	19	gpm	15 gpm required	SS	$54,000	0.6 exponent scale from 100 MTD SCWO Plant
Filter press	27	MT/day	M&EB	CS	$125,000	Vendor quote/engineering judgment
Liquefier/pump	*638*	*gal*	*30 minutes residence time*	*Ti/steel*	*$279,000*	*Estimated from Zimpro vessel*
Heat recovery heat exchanger	0.52	MW	M&EB	C276	$105,000	0.6 exponent scale from 10 MTD SCWO Plant
Gas-fired heater	3.1	MW	M&EB		$310,000	0.6 exponent scale from 100 MTD SCWO Plant
Flue gas heat exchanger	2.2	MW	M&EB	SS	$155,000	Half of fired heater
Reactor	571	gal	1.5 minutes residence time	Alloy 718	$398,000	0.6 exponent scale from MODAR vessel x 2/3
Waste heat boiler	1.1	MW	M&EB	C276	$105,000	0.6 exponent scale from 10 MTD SCWO Plant
Gas/Liquid separator	65	gal	5 min liquid RT, 50% head space	SS	$38,000	0.6 exponent scale from 33 gal vessel
Liquid letdown valve	9	gpm	M&EB	TiN/SS	$16,000	Same as 100 MTD SCWO Plant
System pressure control valve	22	gpm	M&EB	SS	$28,000	0.6 exponent scale from liquid letdown valve
Membrane separator	411,179	scfd	M&EB		$200,000	Phone quote
PSA module	411,179	scfd	M&EB		$200,000	Mann report
Hydrogen storage tank			M&EB		$100,000	Engineering judgment.
Total major equipment					$2,150,000	
Bulk items factor					$2,903,000	1.35 times major equipment cost
Design & fab labor factor					$1,290,000	0.6 times major equipment cost
Control system					$80,000	GA SCWO systems
Facilities					$215,000	0.1 times major equipment cost
Startup cost					$430,000	0.2 times major equipment cost
TOTAL INSTALLED COSTS					$7,068,000	
Notes:						
1. Overall factor on major equipment	3.3					
2. All equipment sizing is at least 20% excess capacity over requirement.						
3. Antal high H2 yields assumed.						
OPERATING COST, $/YR @ 330 ANNUAL OPERATING DAYS						
Item	**Assumption**				**Cost**	**Cost Basis**
Labor	4 operators				$150,000	$18.75/hr
Utilities, etc.	1% of capital cost				$71,000	0.5 SCWO utility costs
Hydrogen credit	$10/GJ; 0.1184 GJ (lower)/kg				$ (371,000)	Mann report values
Steam credit	M&EB values				$ (337,000)	Mann report values
Feed credit	$90/bone dry ton				$ (891,000)	0.75 of Encina disposal cost
TOTAL					($1,378,000)	
IRR @ $120/ton avoided disposal cost						
- Initial investment	($7,068,000)					
- Year 1	$1,378,000	-81%				
- Year 2	$1,378,000	-45%				
- Year 3	$1,378,000	-23%				
- Year 4	$1,378,000	-9%				
- Year 5	$1,378,000	-1%				
- Year 6	$1,378,000	5%				
- Year 7	$1,378,000	8%				
- Year 8	$1,378,000	11%				
- Year 9	$1,378,000	13%				
- Year 10	$1,378,000	14%				