SUPERCRITICAL WATER PARTIAL OXIDATION

PHASE I - PILOT-SCALE TESTING / FEASIBILITY STUDIES
FINAL REPORT

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

JANUARY 2005

PREPARED FOR THE UNITED STATES
DEPARTMENT OF ENERGY
Under Cooperative Agreement
No. DE-FC36-00GO10529

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ABBREVIATIONS AND ACRONYMS

ACS	American Chemical Society
AIChE	American Institute of Chemical Engineers
BCL	Battelle Columbus Laboratory
bdt	Bone dry tons
Btu	British thermal unit
C	Degrees Celsius
C2+	Hydrocarbon gases containing 2 or more carbon atoms
CH_4	Methane
C_2H_6	Ethane
CMC	Carboxymethylcellulose
CO	Carbon monoxide
CO_2	Carbon dioxide
CS	Corn starch
Cs_2CO_3	Cesium carbonate
DOE	Department of Energy
EtOH	Ethanol
GA	General Atomics
GC	Gas chromatography
GJ	Gigajoules
gpm	Gallons per minute
H	Hydrogen
H_2	Hydrogen gas
HHV	Higher heating value
H_2O	Water
ID	Inside diameter
IGT	Institute of Gas Technology
in	inch
L	Liters
LCC	Life cycle cost
LOX	Liquid oxygen
M&EB	Mass and energy balance
MIT	Massachusetts Institute of Technology
MM	Million
MPa	Megapascals
MSW	Municipal solid waste
MTCI	Manufacturing and Technology Conversion International
MW	Megawatts
N_2	Nitrogen
NaCl	Sodium chloride
Ni	Nickel
NO_x	Nitrogen oxides
O_2	Oxygen gas
P	Pressure

PFD	Process flow diagram
PLC	Programmable logic controller
POTW	Publicly owned treatment works
PSA	Pressure swing adsorption
psi	pounds per square inch
RAM	Reliability and maintenance
scfd	Standard cubic feet per day
scfm	Standard cubic feet per minute
SCW	Supercritical water
SCWO	Supercritical water oxidation
SDSU	San Diego State University
SO_x	Sulfur oxides
SS	Sewage sludge
SWPO	Supercritical water partial oxidation
T	Temperature
TOC	Total organic carbon
TP	Time permitting
tpd	English tons per day
UHM	University of Hawaii at Manoa
WM	Wright Malta
wt	Weight

EXECUTIVE SUMMARY

Under Cooperative Agreement No. DE-FC36-00GO10529 for the Department of Energy, General Atomics (GA) is developing Supercritical Water Partial Oxidation (SWPO) as a means of producing hydrogen from low-grade biomass and other waste feeds. The Phase I Pilot-scale Testing/Feasibility Studies have been successfully completed and the results of that effort are described in this report.

The key potential advantage of the SWPO process is the use of partial oxidation in-situ to rapidly heat the gasification medium, resulting in less char formation and improved hydrogen yield. Another major advantage is that the high-pressure, high-density aqueous environment is ideal for reacting and gasifying organics of all types. The high water content of the medium encourages formation of hydrogen and hydrogen-rich products and is especially compatible with high water content feeds such as biomass materials. The high water content of the medium is also effective for gasification of hydrogen-poor materials such as coal.

A versatile pilot plant for exploring gasification in supercritical water has been established at GA's facilities in San Diego. The Phase I testing of the SWPO process with wood and ethanol mixtures demonstrated gasification efficiencies of about 90%, comparable to those found in prior laboratory-scale SCW gasification work carried out at the University of Hawaii at Manoa (UHM), as well as other biomass gasification experience with conventional gasifiers. As in the prior work at UHM, a significant amount of the hydrogen found in the gas phase products is derived from the water/steam matrix. The studies at UHM utilized an indirectly heated gasifier with an activated carbon catalyst. In contrast, the GA studies utilized a directly heated gasifier without catalyst, plus a surrogate waste fuel. Attainment of comparable gasification efficiencies without catalysis is an important advancement for the GA process, and opens the way for efficient hydrogen production from low-value, dirty feed materials.

The Phase I results indicate that a practical means to overcome limitations on biomass slurry feed concentration and preheat temperature is to coprocess an auxiliary high heating value material. SWPO coprocessing of two high-water content wastes, partially dewatered sewage sludge and trap grease, yields a scenario for the production of hydrogen at highly competitive prices. It is estimated that there are hundreds if not thousands of potential sites for this technology across the US and worldwide.

The economics for plants processing 40 tpd sewage sludge solids augmented with grease trap waste are favorable over a significant range of cost parameters such as sludge disposal credit and capital financing. Hydrogen production costs for SWPO plants of this size are projected to be about $3/GJ or less. Economics may be further improved by future developments such as pumping of higher solids content sludges and improved gasifier nozzle designs to reduce char and improve hydrogen yields. The easiest market entry for SWPO is expected to be direct sales to municipal wastewater treatment plants for use with sewage sludge in conjunction with trap grease, as both of these wastes are ubiquitous and have reasonably well-defined negative value (i.e., the process can take credit for reduction of well-defined disposal costs for these

streams). Additionally, waste grease is frequently recovered at municipal wastewater treatment plants where it is already contaminated with sewage.

SWPO should also be favorable to other market applications in which low or negative value, high water content biomass is available in conjunction with a low or negative value fuel material. For biomass slurries primary candidates are sewage sludge, manure sludge, and shredded and/or composted organic municipal solid waste (MSW) slurries. For the high heating value stream primary candidates are trap grease, waste plastic or rubber slurries, and coal or coke slurries.

Phase II of the SWPO program will be focused on verifying process improvements identified during Phase I, and then performing extended duration testing with the GA pilot plant. Tests of at least 100 hours duration using sewage sludge and trap grease as simultaneous feedstocks are a primary objective. Follow-on Phases III and IV of the SWPO program will develop and demonstrate a dedicated 5 tpd reduced-scale SWPO facility at a location such as the Encina municipal wastewater treatment plant. Subsequent to this demonstration, the technology will be ready for a commercial-scale demonstration.

While there are clearly technical challenges that must still be addressed, SWPO represents an outstanding opportunity to further the dual goals of developing a hydrogen economy and practicing environmentally friendly waste disposal. It may well represent one of the few scenarios in which hydrogen may be produced economically from biomass at a relatively small scale. SWPO could thus play a pivotal role in the proliferation of distributed hydrogen generation.

1. INTRODUCTION

Under Cooperative Agreement No. DE-FC36-00GO10529 for the Department of Energy, General Atomics (GA) is developing Supercritical Water Partial Oxidation (SWPO) for efficient and environmentally attractive gasification and hydrogen production from low-grade biomass materials. In particular biomass materials such as thickened sewage sludge solids, grease trap waste and sorted municipal solid waste (MSW), as well as low-grade fossil fuels such as high-sulfur coal and petroleum coke, are targeted for distributed generation of hydrogen close to population centers.

SWPO involves carrying out oxidative reactions in the supercritical water (SCW) environment – akin to high-pressure steam – in the presence of sub-stoichiometric quantities of oxidant, typically pure oxygen or air. A key advantage anticipated for the SWPO process is the use of partial oxidation in-situ to rapidly heat the gasification medium, resulting in less char formation and improved hydrogen yield. Another major advantage of SWPO is that the high-pressure, high-density aqueous environment is ideal for reacting and gasifying organics. The high water content of the SWPO medium encourages formation of hydrogen and hydrogen-rich products and is very compatible with high water content feeds such as biomass materials. By the same token, the high water content of the SWPO medium is effective for gasification of hydrogen-poor materials such as coal. Further background information on the SWPO process may be found in Appendix A.

The overall goals and objectives of the SWPO development program are to develop and commercialize a technology to convert biomass, waste materials such as treated or untreated sewage sludge solids, sorted MSW such as plastics and rubber, and low grade fossil fuels such as petroleum coke and high-sulfur coal to hydrogen. The emphasis of the development program is to focus on low- and negative-value municipal wastes that are currently costly and troublesome to dispose of. In particular, sewage sludge solids (SSS) are targeted as a primary feedstock for SWPO to offset the current high cost of disposal. Many municipalities pay over $200 per dry ton for disposal of treated SSS, also referred to as biosolids. The SWPO program is targeting primary and secondary sewage sludge solids, before final treatment and disposal as biosolids, with operational cost savings in addition to avoided disposal costs. This cost-savings incentive is an important factor in achieving competitive hydrogen production costs using SWPO.

SWPO is ideally suited for processing wet biomass wastes such as SSS. Unlike other gasification technologies, feedstocks do not have to be dried before feeding to SWPO. Thus, pretreatment costs can be minimized for wet biomass feeds. Many wet biomass feeds cannot be slurried and pumped at concentrations much above about 12 wt% dry solids. To overcome this limitation, a higher heating value fuel such as waste grease must be co-fed to SWPO along with the wet biomass in order to achieve desired gasification temperatures and hydrogen yields. Other example candidate waste fuels for co-feeding with wet biomass feeds are slurried plastics and rubber, which can be acquired as sorted MSW, and slurried coal or petroleum coke.

A multiphase SWPO development program is planned to perform feasibility studies, pilot-scale tests, system integration and reduced-scale demonstration at a selected wastewater treatment facility, and finally commercial-scale SWPO. This 9 year development program is nearing the end of its third year with the completion of this Phase I final report. For Phase I the tasks performed and reported on herein are as follows:

Task 1: Pilot-Scale Preliminary Testing

- Perform SWPO testing on biomass fuels and coal.

Task 2: Pilot-scale Design and Analysis

- Perform pilot-scale conceptual design of SWPO system for Phase II development.

- Perform system engineering evaluation to predict when and how hydrogen production goals can be met.

Task 3: Development Plan

- Prepare a SWPO development plan, including cost and schedule estimate.

- Prepare a business plan to identify SWPO market potential.

- Define follow-on activities from preliminary testing through pilot-scale demonstration of an integrated SWPO system.

This report presents the results of the Phase I work. Section 3 describes the Phase I testing, Section 4 presents the pilot-scale design and analysis, and Section 5 presents the development plan, including a description of the Phase II through Phase IV follow-on efforts. Finally, Section 6 presents the Phase I conclusions.

2. TASK 1: PRELIMINARY PILOT-SCALE TESTING

SWPO tests were performed to explore the use of partial oxidation in-situ to rapidly heat the gasification medium in order to reduce char formation and improve hydrogen yields. A test plan was prepared at the start of testing in April, 2001. This document is included as Appendix B, although the experimental matrix evolved considerably from the original plan.

2.1. TEST DESCRIPTION

The testing was performed using GA's pilot plant, shown in Figures 2-1 through 2-5. Figure 2-1 shows the liquid pumping skid, while Figure 2 shows the slurry pumping skid.

A number of different gasifier configurations were tested over the course of the Phase I effort. Figure 2-3 shows two of the gasifiers used during earlier testing, the "small" downflow vessel gasifier (labeled "small vessel reactor" in Figure 2-3, volume about 4 liters), and the horizontal tube gasifier (labeled "tube reactor" in Figure 2-3, volume about 9 liters). The bulk of the testing was carried out with the "large" downflow vessel gasifier, shown in Figures 2-4 and 2-5. The gasifier reactor is covered by insulation, although the gasifier top head is visible above the insulation. This gasifier has a volume of about 10 liters, and at the flow rates tested provides a gas residence time of about 75 seconds at 650°C operating temperature and about 60 seconds at 800°C operating temperature. Solids (feed particulates, ash and char) can potentially have a much lower residence time by falling at terminal velocity through the vessel, and most tests incorporated one or more screens or baffles to prevent such gasifier short circuiting.

Figure 2-6 provides a simplified SWPO process flow diagram illustrating the primary process features. In this figure, the "SWPO reactor" is the gasifier.
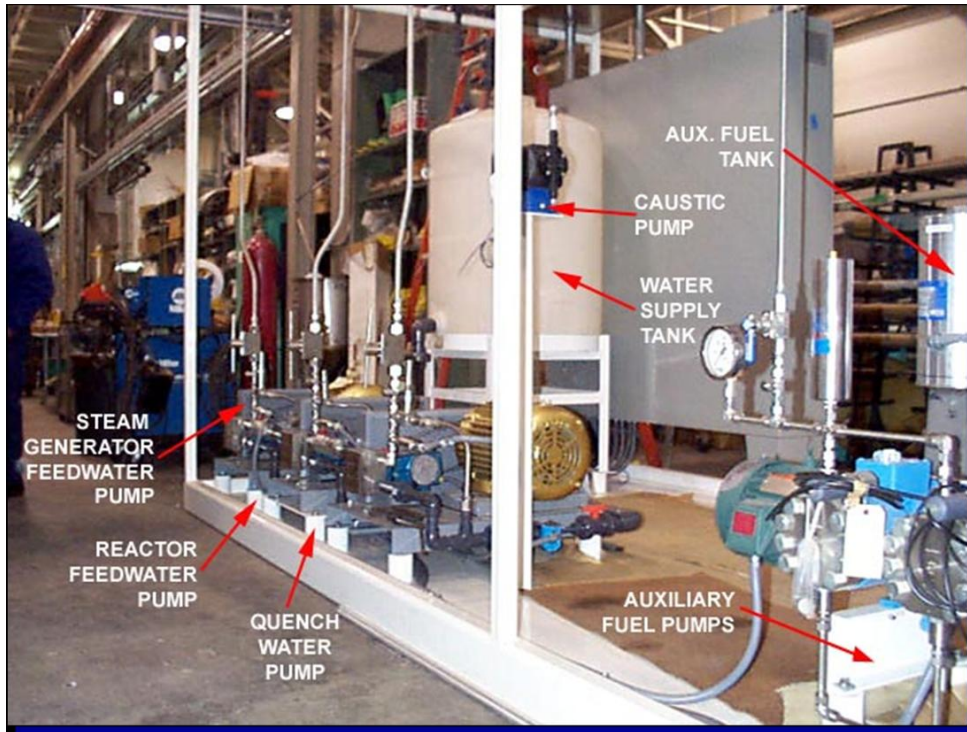
Figure 2-1. SWPO pump skid
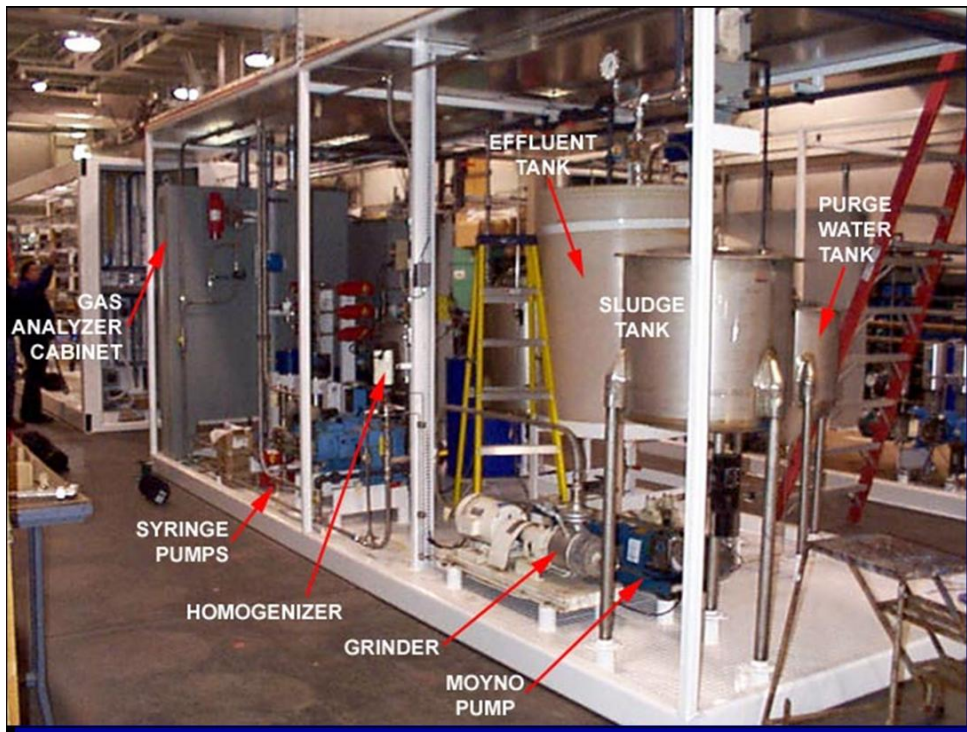
Figure 2-2. SWPO slurry and effluent skid.
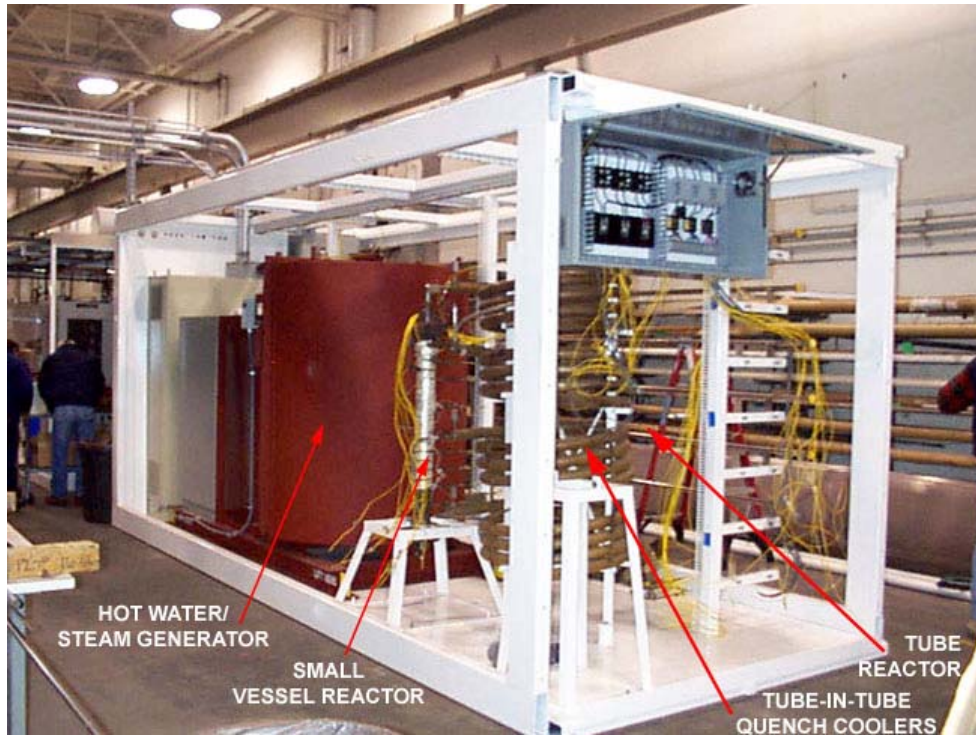
Figure 2-3. SWPO reactor skid showing small vessel gasifier and tube gasifier.

Figure 2-4. SWPO reactor skid with shielding and large vessel gasifier installed.

Figure 2-5. SWPO large vessel gasifier.
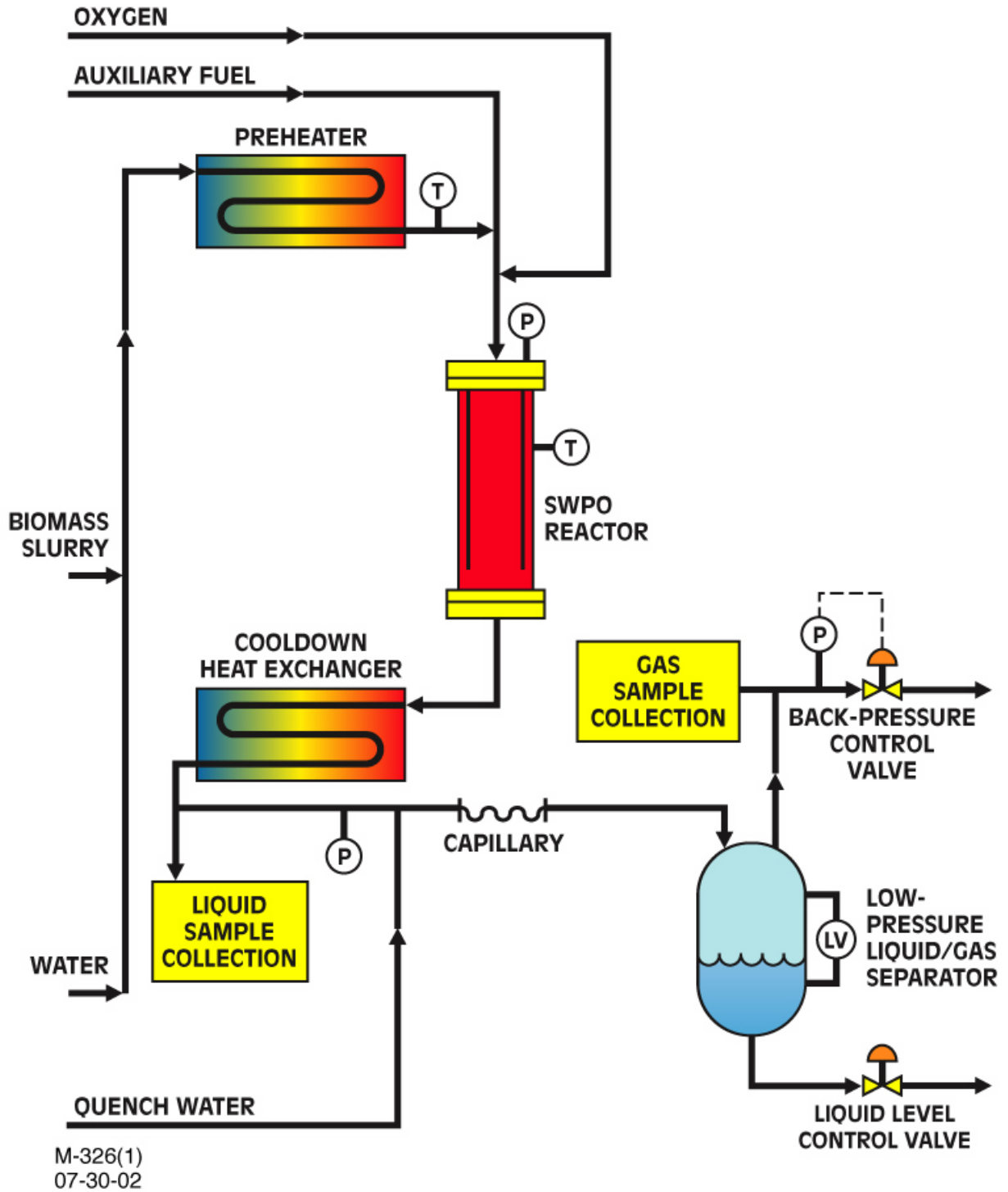
Figure 2-6. Simplified SWPO process flow diagram.

OXYGEN

AUXILIARY FUEL

PREHEATER

T

P

SWPO
REACTOR

T

BIOMASS
SLURRY

COOLDOWN
HEAT EXCHANGER

GAS
SAMPLE
COLLECTION

P

BACK-PRESSURE
CONTROL
VALVE

CAPILLARY

P

LIQUID
SAMPLE
COLLECTION

LOW-
PRESSURE
LIQUID/GAS
SEPARATOR

LV

WATER

QUENCH WATER

LIQUID LEVEL
CONTROL VALVE

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Figure 2-7 provides a more detailed SWPO process flow diagram (PFD) for the gasification tests carried out with the large vessel gasifier. Dual syringe pumps are used to deliver high pressure slurry to the system. Pressurized slurry is fed to the preheater where it is preheated to a temperature of about 250°C. An auxiliary fuel is also necessary to help attain the desired gasifier operating temperature. Ethanol was used as the auxiliary fuel during Phase I. In actual practice, this auxiliary fuel would be a co-feed of high heating value waste such as trap grease or slurried plastic, rubber, or coal. As shown in Figures 2-6 and 2-7, high-pressure auxiliary fuel (ethanol) and oxygen are combined with the preheated slurry at the gasifier inlet. Dependent upon the quantity of oxygen provided, oxidation of a portion of the organic feeds results in a nominal gasifier temperature of 650-800°C. In the gasifier, the organic feed is converted primarily to CO_2, H_2O, H_2, CH_4 and CO.

The gasifier effluent is cooled to near ambient temperature by a series of annular heat exchangers. Pressure control water is introduced and the stream passes through a capillary to be depressurized to slightly above atmospheric pressure. The flow of the pressure control water is varied to maintain the gasifier at the desired pressure of 3400 psi. Following depressurization, the effluent is phase separated in a low pressure gas-liquid separator. Level control in the phase separator is aided by the introduction of a low flow of air from an air cylinder. Liquid effluent pH and conductivity are measured on-line in the effluent line. The liquid effluent is then collected in a tank, while the gases are vented through the facility carbon filter and released to the atmosphere. Liquid effluent samples are collected either just downstream of the cooldown heat exchanger or from the drain line of the effluent collection tank. The effluent gas is monitored online upstream of the carbon filters for CO_2, H_2, CH_4, CO, and O_2 content.

Table 2-1 provides a synopsis of the Phase I pilot-scale testing carried out. All tests were carried out at 3400 psi. As previously mentioned, 3 different gasifiers were used in the course of the testing. As shown in Table 2-1, several runs with a composted mixture of municipal solid waste (MSW) and SSS were carried out with a tube gasifier in the absence of oxidant, i.e., they were indirectly heated and did not utilize partial oxidation. The tube gasifier had an ID of 0.815 in. and a length of about 90 feet. The composted MSW/SSS was a product of the Bedminster composting process. In the large downflow vessel tests, a "J-screen" was frequently utilized to help increase the residence time of solid particles. A J-screen is essentially a rugged filter plate or grate made from two layers of bars at right angles to one another. The J-screens helped retain larger particles in the gasifier while allowing the process fluid and smaller particles to pass through.
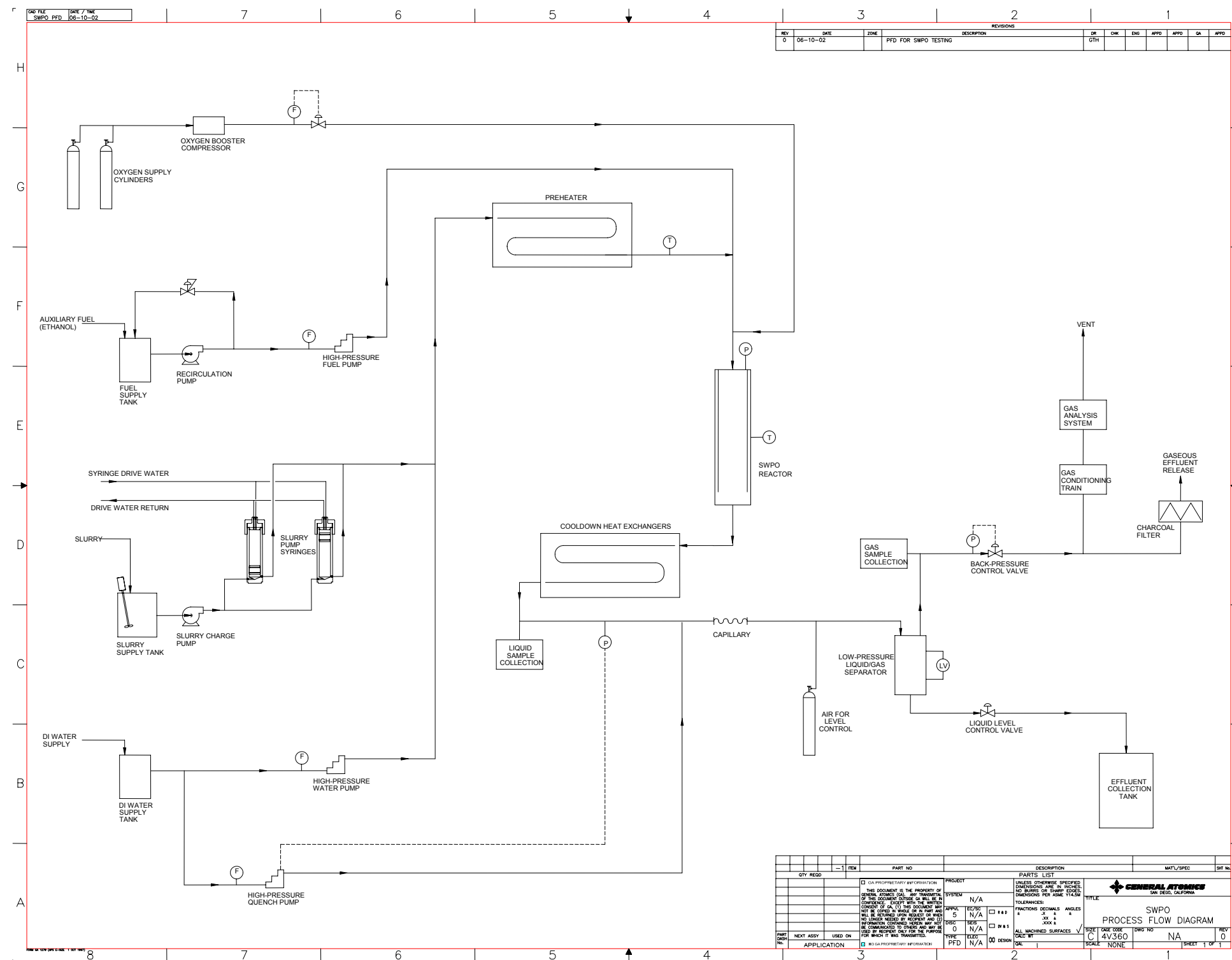
Figure 2-7. GA SWPO pilot plant process flow diagram (PFD).

TABLE 2-1. SUMMARY OF GASIFICATION RUNS

Feed	Run Dates	Gasifier Type	System Configuration	Run Conditions	Results
40% corn starch	6/19/01	Small vessel (volume ~4L)	Mixing tee – premix feed and SCW to rapidly heat feed.	605°C	Significant char formation, insufficient gasification temperature.
40% coal	6/28/01; 7/2/01	Small vessel	Mixing tee – premix feed and SCW to rapidly heat feed.	530°C; 620°C	Insufficient temperature and solids residence time resulting in poor gasification of coal.
30-40% MSW/SS compost	8/16/01	Small vessel	Mixing tee – premix feed and SCW to rapidly heat feed.	570°C	Too much supercritical dilution water at too low a temperature and oxidation of nearly all the feed, resulting in low gasification temperatures and poor gasification yields.
30-40% MSW/SS compost	10/12/01; 10/31/01; 11/8/01; 11/19/01; 1/3/02	Pipe (volume ~9L)	Pipe preheater, no oxidant	620°C-650°C	Preheat T < 400°C necessary to avoid charring
30% corn starch	1/30/02	Pipe	Pipe preheater, air oxidant	650°C, 300°C preheat	Preheat T < 300°C necessary to avoid charring
10% wood + 10% coal + ethanol (EtOH)	3/18/02; 3/21/02	Large vessel (volume ~10L)	Gasifier baffle; gasifier mid-screen	800°C, 250°C preheat	Poor mixing and insufficient solids residence time resulting in poor gasification of coal and rapid buildup of char
10% wood + EtOH	4/10/02	Large vessel	J-screens at gasifier middle and bottom	650°C, 250°C preheat	Successful run. Good hydrogen yield.
10% wood + EtOH	4/12/02	Large vessel	J-screen at gasifier bottom	650°C, 250°C preheat	Successful run. Good hydrogen yield.
10% wood + EtOH	4/17/02	Large vessel	J-screen at gasifier bottom	800°C, 250°C preheat	Successful run. Good hydrogen yield.
10% wood + EtOH	4/18/02	Large vessel	No J-screens	800°C, 250°C preheat	Successful run. Good hydrogen yield.
10% wood + EtOH	4/23/02	Large vessel	No J-screens	650°C, 250°C preheat	Successful run. Good hydrogen yield.
10% wood + EtOH	4/24/02	Large vessel	No J-screens	800°C, 250°C preheat	Successful run. Good hydrogen yield.
10% corn starch + EtOH	4/25/02; 4/26/02; 4/30/02; 5/3/02	Large vessel	Various J-screen positions	650°C	Corn starch can only be preheated to 70°C to avoid thickening and preheater plugging.
High solids feeds (40% corn starch, 15% wood, 20% MSW/SSS compost) + EtOH	5/8/02; 5/14/02, 5/15/02;5/16/02, 5/17/02	Large vessel	J-screen at gasifier bottom	650°C	40% corn starch plugs preheater even at 70°C. First use of new suspending agent (commercial gum) leads to pumping problems with 15% wood. Poor nozzle dispersion leads to char buildup and plugging at gasifier bottom with MSW/SSS compost.

The tests listed in Table 2-1 summarize the chronological progress that was made during Phase I. A number of problems or limitations were encountered and overcome in the course of testing, culminating in a series of wood flour plus ethanol co-feed gasification runs with good hydrogen yields. Finally, additional tests were performed with corn starch (as a reference material), wood and MSW/SSS in attempting to increase the solids content of the biomass feeds, but without much success. The following section provides further discussion of the Phase I tests in Table 2-1 and their impact on the technology development.

2.2. TEST RESULTS AND DISCUSSION

<u>Slurry Pumping</u>

Reliable high-pressure pumping of heavy biomass slurries is an essential requirement of the SWPO process. In the dual syringe pump developed by GA under other programs, clean water is pumped to the top side of a piston located within a cylindrical vessel, forcing the slurry below the piston into the SWPO system. When the cylinder is depleted of slurry, it is switched offline and refilled using a low pressure pump. Meanwhile, a second cylinder is providing feed to the system, allowing for continuous feed flow. The continuous slurry delivery is facilitated by computer sequenced ball valves. The dual syringe pump has an advantage over a typical reciprocating pump because the valves are only cycled about once every 5 minutes, rather than once a second for the check valves in reciprocating pumps, thus minimizing valve wear and fouling. In addition, powered actuation of these ball valves provides better assurance of proper operation than do conventional check valves, which rely on gravity or the action of a light spring.

Building on significant prior experience with pumping heavy wood/plastic slurries with dual syringe pumps, substantial additional effort was made during Phase I to improve the reliable operation of the dual syringe pumps on the pilot system. A number of improvements over the basic design were implemented, including magnetic sensing of the position of the driving pistons. The pump now operates in highly reliable fashion.

The maximum pumpable concentration of wood flour slurries achieved during Phase I was 10 wt% wood with 10% moisture content, or 9 wt% wood on a dry basis. These slurries utilized 2.5 wt% carboxymethylcellulose (CMC) as a suspension agent, for a total slurry solids content of about 11.5 wt%. During testing, there were indications that wood flour slurries of at least 14 wt% would be pumpable with a bit of optimization work. The maximum pumpable concentration of composted MSW/SSS was in the range of 30 wt% dry basis. Also, 9 wt% wood + 10 wt% coal (dry basis) was readily pumpable. To attain higher biomass solids content than can be pumped, alternate methods are being considered.

Feed Heatup

Energy recovery and feed preheating are important elements in the development of SWPO. The GA pilot plant was initially set up with a mixing tee to rapidly heat the incoming biomass feed slurry by mixing with supercritical water. This proved to be problematic because the supercritical water preheat temperature was limited by tube strength to about 650°C and so a relatively large amount of supercritical water was required. The biomass slurry was thereby diluted and oxidation of most of the biomass was required to attain the desired final gasifier temperature. It was also found that biomass feed slurry could not be preheated to near gasifier temperature in a heat exchanger without charring and plugging. It was found that preheat temperatures in excess of about 250°C are conducive to charring with wood slurry feeds. Preheating of corn starch is even more limited as it thickens and plugs quickly above about 60°C. By slowly precooking cornstarch to form a paste, UHM was able to preheat corn starch to higher temperatures, but this process is not suitable for production operations. With limited biomass preheating up to 250°C, limited SCW preheating up to 650°C, and limited biomass feed concentration of 10-15 wt%, insufficient biomass is available after partial oxidation to achieve economically viable hydrogen production. As previously mentioned and as further discussed below, a combination of preheat and partial oxidation utilizing a high heating value auxiliary fuel co-feed was finally utilized to attain acceptable gasification results.

Gasifier Type

Gasifier type and performance are essential elements for the development of the SWPO process. As noted in Table 3, both downflow vessel and horizontal tube gasifiers have been tested. A tube gasifier has less backmixing than a vessel gasifier, and is less prone to short circuiting or flow bypass, but is limited in temperature by tube strength and has higher heat losses than a vessel gasifier. Based on the Phase I tests and other information, a vessel gasifier now appears to be preferable to a tube gasifier. A vessel gasifier allows better temperature control and better heat conservation, and is amenable to the use of a corrosion resistant thermal sleeve. With such a thermal sleeve the reaction zone can be maintained at a temperature considerably above the allowable temperature of the pressure vessel. During Phase I, a thermal sleeve allowed tests to be conducted at 800°C. Even higher temperatures are possible with this gasifier type. Reduction of gasifier surface area to reduce heat loss is a primary driver in the trend to pressurized gasifiers in coal gasification. This factor is likewise of key importance in biomass gasification, and is best achieved with a vessel gasifier.

One area of potential improvement in the performance of GA's downflow vessel gasifier is in the design of the feed injector nozzle. In the Phase I tests described here, a relatively large nozzle orifice of 0.180-in. diameter was used to minimize the chance of nozzle plugging for a variety of slurried feedstocks. This resulted in a relatively slow velocity and poor dispersion of the feed entering the gasifier. Based on test observations, it is believed that the feed nozzle was overly large in orifice size, and that as a result relatively large globules of feed material were able to fall through the gasifier with insufficient opportunity to disperse and react. This in turn could result in char and tar formation and incomplete gas-phase reactions. Thus, future testing will evaluate a smaller nozzle orifice diameter with a higher feed injection velocity.

Paragraph deleted due to proprietary content.

Thus, with modest improvements in GA's vessel gasifier design, improvements in gasification efficiencies and reduction of tar and char formation are likely. Future testing during Phase II will evaluate these improvements in vessel gasifier performance.

Feed Type

The SWPO process is ideally suited to wet, dirty feed materials that have low or negative value, and can improve the economics of hydrogen production. Several feed types were evaluated during Phase I, including corn starch as a reference feed for comparison with other studies. As shown in Table 1, a number of runs were carried out with corn starch feed at concentrations of 10 to 40 wt%. All of these compositions were prone to thickening and plugging in the preheater at temperatures as low as 70°C, which prevented the collection of satisfactory gasification data. One purpose of the corn starch runs was to allow comparison with laboratory-scale data from UHM. UHM (1999) reported no gasifier plugging at about 10 wt% corn starch and plugging at about 14 wt% corn starch, although the plugging is attributed to char formation as opposed to thickening during preheat. Thickening and char formation are probably related, though, as thickening during preheating results in solid agglomerations that are prone to char formation upon entry into the gasifier. It is notable that at 10 wt% corn starch, preheater plugging occurred in the GA pilot tests but not in the UHM laboratory-scale tests. This is thought to be due to the fact that the corn starch was precooked into a paste in the UHM tests.

Composted MSW/SSS available from the Bedminster Process and other similar composting processes was tested during Phase I as a good source of size-reduced feed for supercritical water gasification, minimizing the need for front end processing (shredding, grinding, etc.). Composted MSW/SSS can be pumped at over 30 wt% (dry basis), sufficient to support partial oxidation and gasification without the addition of coal or other auxiliary fuel. By contrast, sewage sludge and uncomposted sawdust or wood flour can only be pumped at concentrations between 10-15 wt% (dry basis) maximum. Despite the pumpability of high solids content composted slurries, the advantages of composted MSW/SSS are offset by several factors. During composting, the organic material becomes depleted in hydrogen and heating value due to microbial action (aerobic digestion). This works against high hydrogen production. Compost also has a fairly high content of minerals and grit that are parasitic to the SWPO process and complicate grinding, pumping, heat exchange and pressure letdown in a SWPO system. Furthermore, a composter front end is expensive, adversely affecting the economics of the SWPO process, unless a composter already exists at the site.

Paragraphs deleted due to proprietary content.

SWPO of Wood Slurries

As noted earlier, Phase I testing was eventually focused on SWPO of wood slurries. Table 2-2 summarizes the tests carried out. Auxiliary fuel in the form of ethanol was used in these tests. Tests were carried out at both 650°C and 800°C nominal gasifier temperature. Run duration was approximately 4 hours. Conversion of carbon to gaseous products was incomplete, as indicated by the liquid (tar) and solid (char) products shown in Table 2-2. Much of this incomplete conversion is believed to be due to insufficient dispersion at the feed injection nozzle and insufficient solid particle residence time. Poor dispersion at the nozzle is consistent with the finding of unused O_2 in the gaseous effluent from the gasifier. About one third of the oxygen in the effluent gas is residual oxidant, while the remainder is from the air introduced at the gas-liquid separator to stabilize separator level control. Future tests during Phase II will include improvements in nozzle design and solid particle residence time, as discussed earlier.

Carbon balances in Table 2-2 are fairly good, in the range of 90%. At least some of the missing mass is likely due to residual tar or char that was distributed in different parts of the system and difficult to collect. Improvements are planned for Phase II to provide clean-out access at various locations that will enable char removal between tests to improve the mass balances. The SWPO gasification results in Table 2-2 are interpreted and compared to results from other gasifiers in Section 3.3.

TABLE 2-2. SUMMARY OF 9% WOOD GASIFICATION RUNS

Run Date:	4/10/2002	4/12/2002	4/17/2002	4/18/2002	4/23/2002	4/24/2002
Feed (dry basis)	9% wood	9% wood	9% wood	9% wood	9% wood	9% wood
Gasifier internal features[1]	2 J-screens	1 J-screen	1 J-screen	No J-screen	No J-screen	No J-screen
Gasifier T, C	650	650	800	800	650	800
Input						
Run time min	105	250	242	195	128	132
Oxygen g/min	109	104	110	112	86	113
Stoich. EtOH g/min	52.2	49.8	52.7	53.7	41.2	54.1
Excess EtOH g/min	16.8	22.2	10.3	3.3	17.8	7.4
Feed g/min	367	345	350	336	330	347
CMC %[2]	2.5	2.5	2.5	2.5	2.5	2.5
Output						
Gas SCFM	4.5	5.1	4.6	4.7	4.3	4.9
H_2 %	18.6	21.1	17.0	18.8	25.3	16.9
CH_4 %	16.3	16.7	13.6	14.9	15.7	13.3
C_2H_6 %	0.1	0.1	0.1	0.1	0.2	0.1
CO %	2.7	2.9	1.9	2.2	4.1	1.7
CO_2 %	48.6	48.6	54.5	48.7	43.7	54.9
N_2 %	10.4	8.0	9.5	11.2	8.1	9.7
O_2 %	3.5	2.7	3.5	4.1	3.0	3.5
% Feed C in solid (char)	6.9	2.7	3.5	2.7	0.5	0.2
% Feed C in liquid (tar)	2.3	2.9	6.0	0.0	8.7	5.0
Carbon balance %	79	88	90	90	83	94

Notes:
(1) – J-screens were used to increase solid particle residence time.
(2) – CMC is a suspension agent to prevent settling in the feed slurry.

Figures 2-8 through 2-11 show sample traces of key variables for runs at maximum reactor temperatures of about 650°C and 800°C. The temperature traces in Figures 2-8 and 2-10 are considerably more erratic than is typical for SCWO. This is believed to be an effect of insufficient nozzle dispersion. In both cases, there was significant char and ash buildup in the gasifier that likely contributed to more erratic temperature fluctuations later in the run. Better mixing is expected to reduce the temperature fluctuations considerably.

As shown in Figures 2-9 and 2-11, gaseous effluent from the system was monitored by online gas meters. In addition, grab samples were also checked by gas chromatography (GC) in the laboratory. In general the results of the GC and online meters were within 10% of one another, the only significant difference being that CO from the online infrared meter is erroneously high due to interference from CO_2 and CH_4. The GC results have been used for Table2-2. The presence of nitrogen in the effluent gas is primarily due to the diluting air stream used to aid in level control at the low pressure gas-liquid separator.

The results of the wood slurry plus ethanol auxiliary fuel tests confirmed that SWPO is a viable means of gasification and hydrogen production without the need for catalysts. Future work during Phase II will focus on improving SWPO performance and verifying long-term operability without plugging.
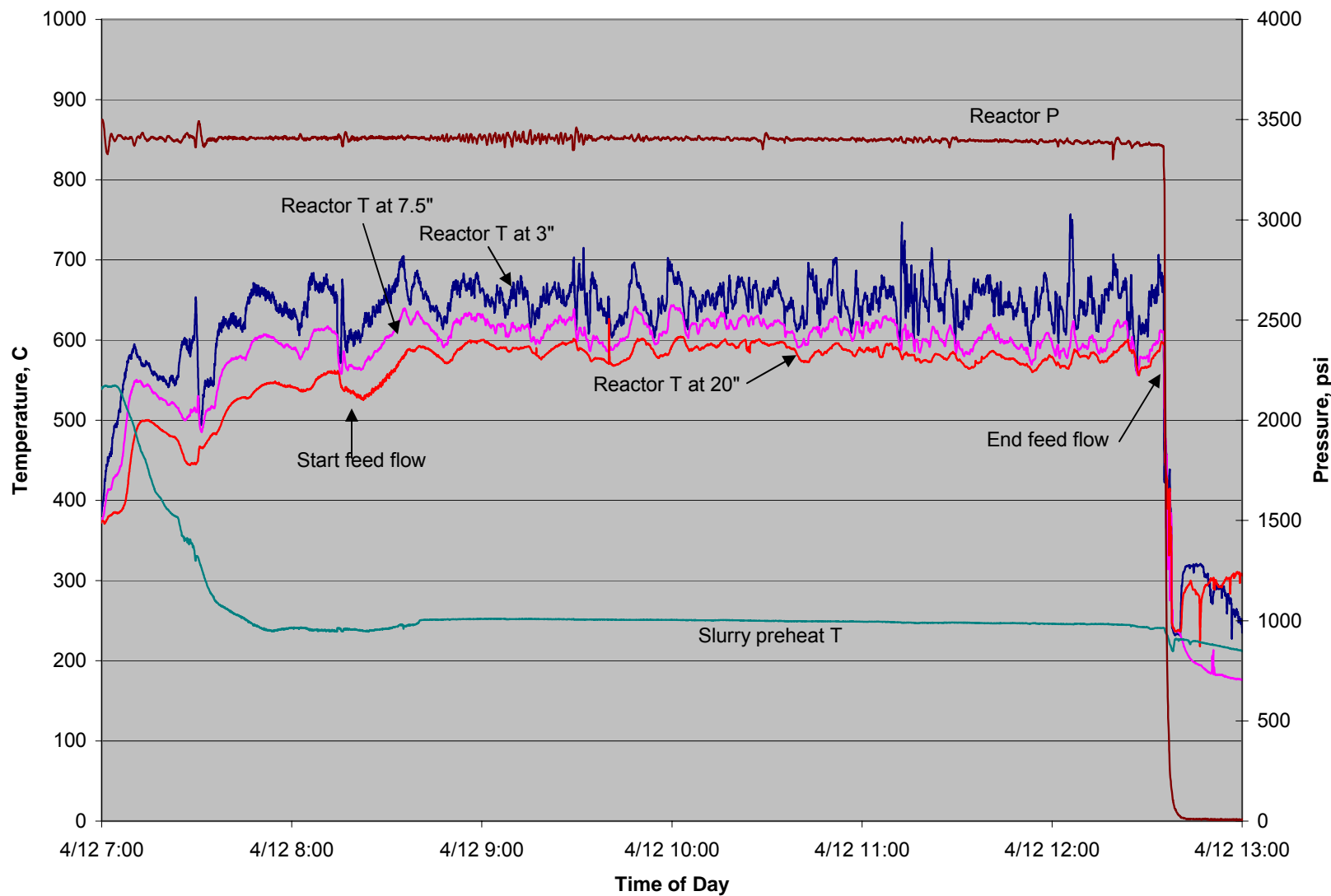
Figure 2-8. Temperature and pressure traces for SWPO run at 650°C.
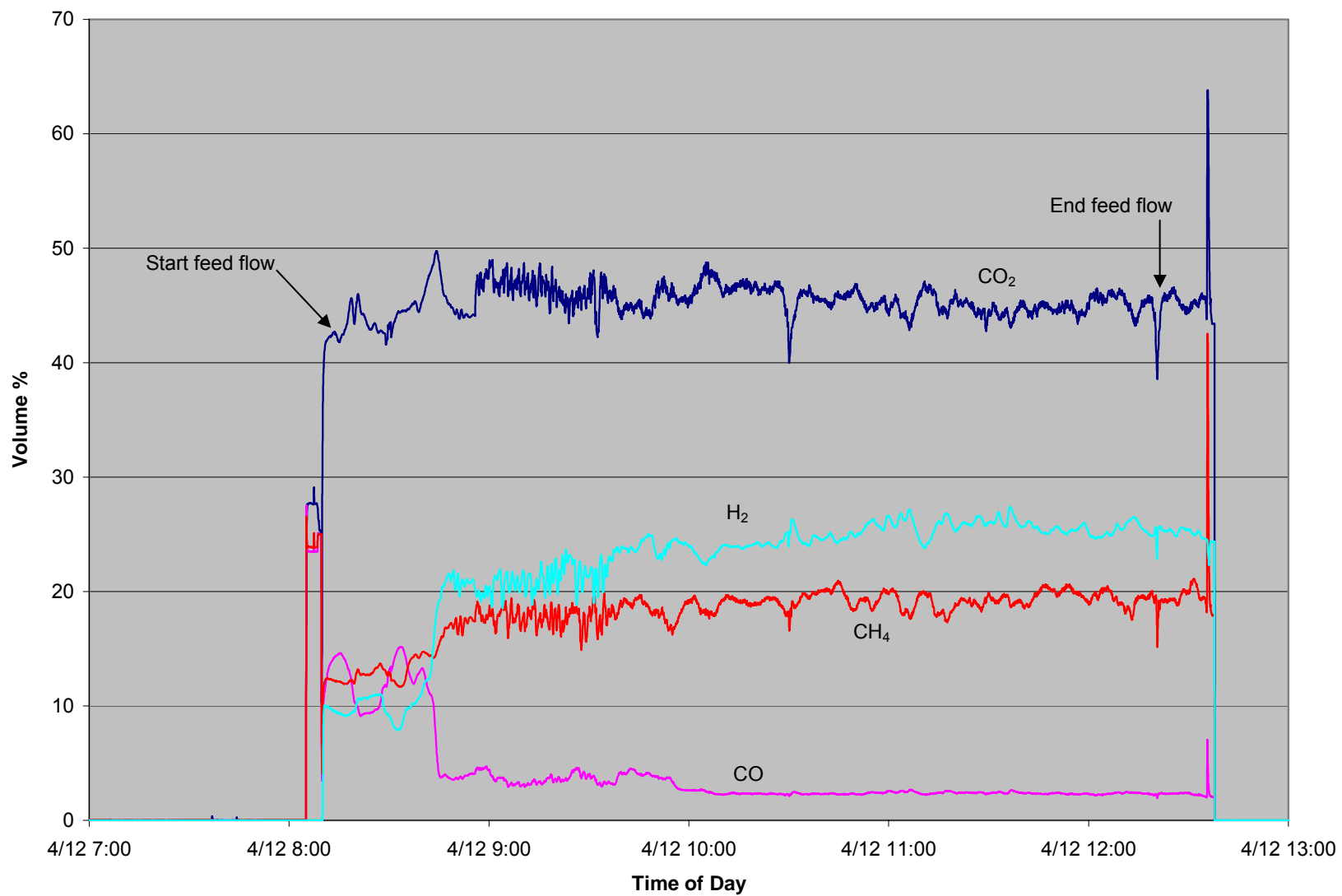
Figure 2-9. Gas analyzer traces for SWPO run at 650°C.
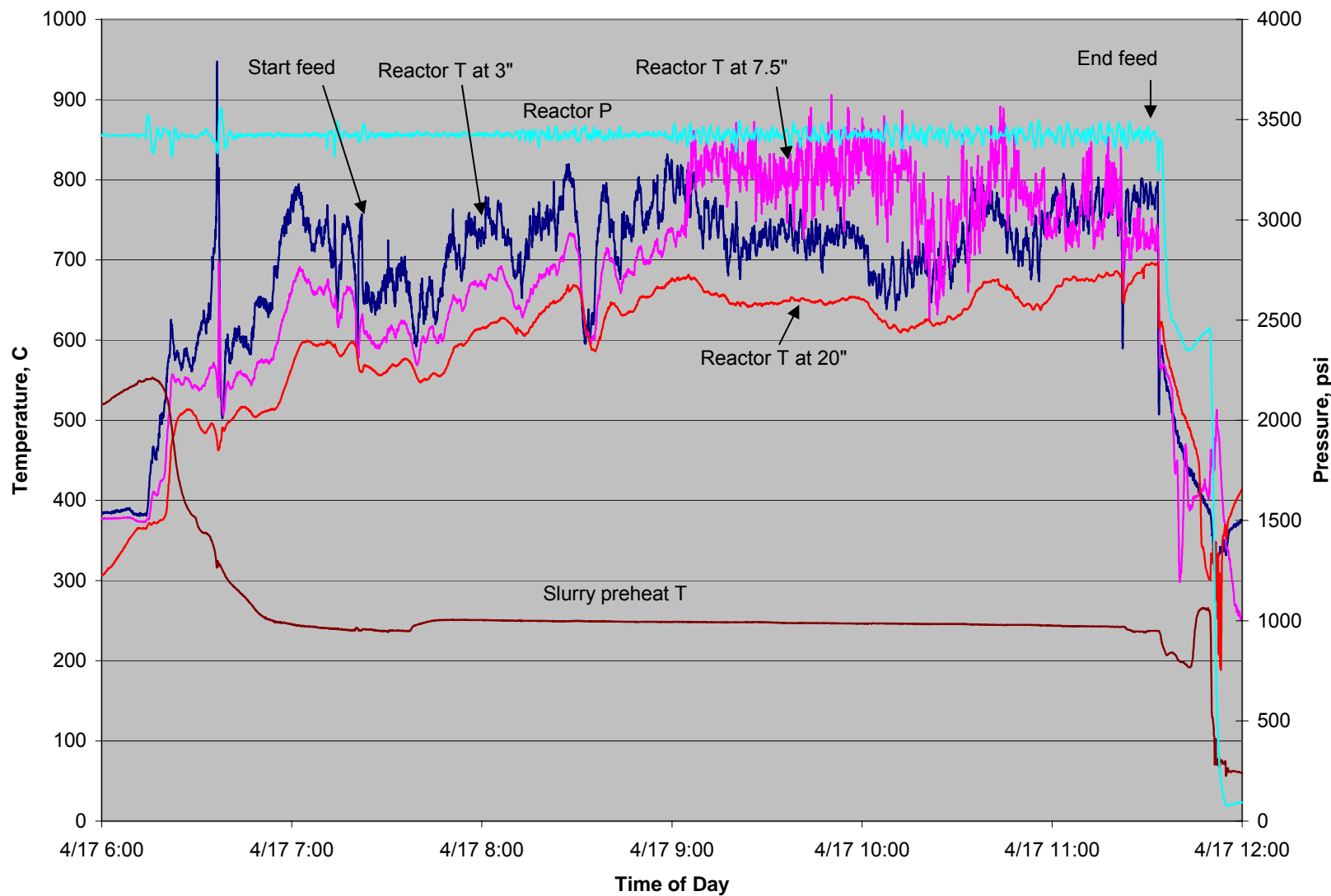
Figure 2-10. Temperature and pressure traces for SWPO run at 800°C.
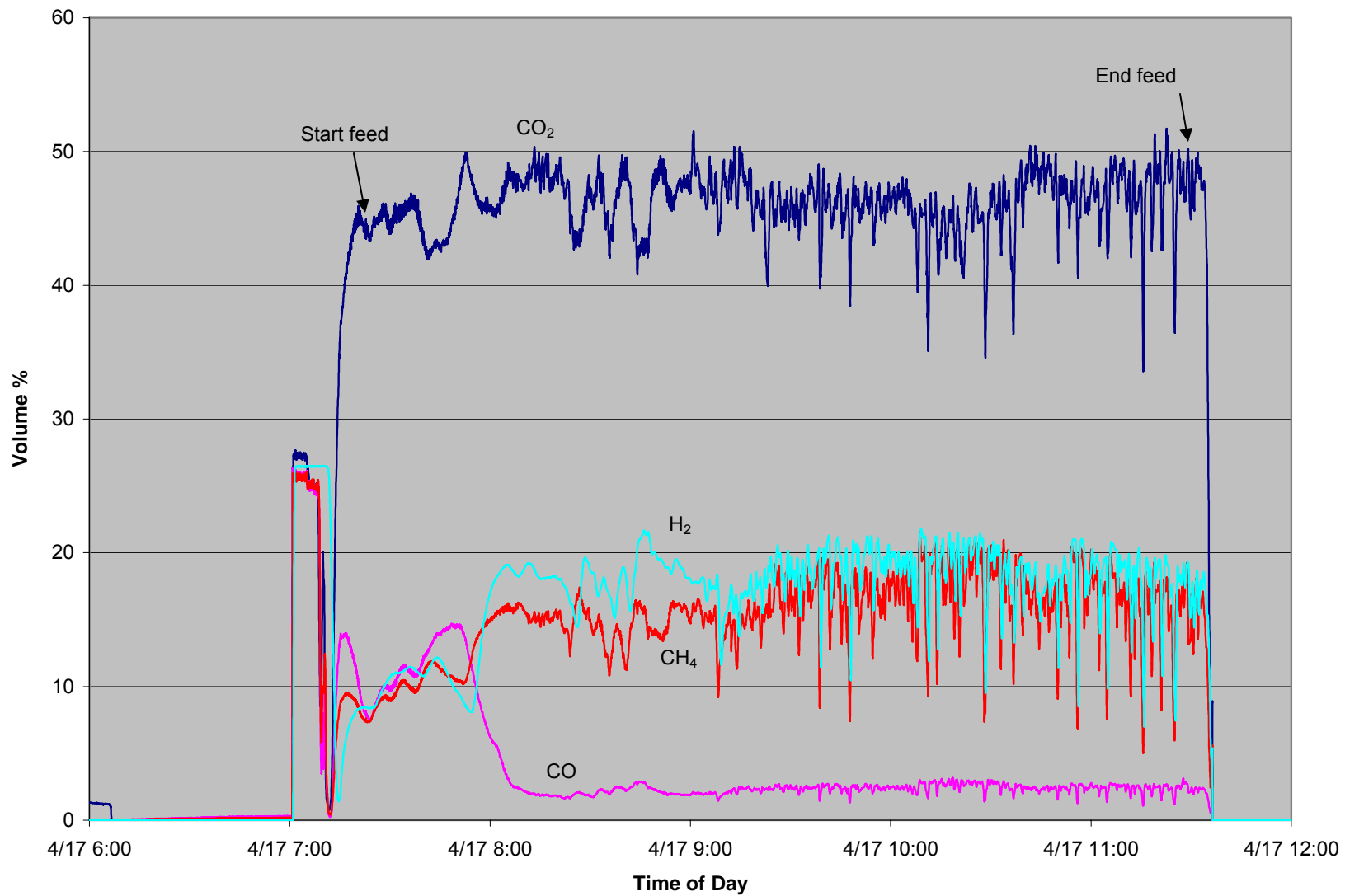
Figure 2-11. Gas analyzer traces for SWPO run at 800°C.

Equilibrium Calculations

Figures 2-12 and 2-13 compare the measured SWPO gasifier exit composition with the computed equilibrium composition as predicted by the Stanjan chemical equilibrium program (available on the web for example at http://grashof.engr.colostate.edu/tools/equil.html) at temperatures of 650°C and 800°C, respectively. The figures also show the expected effect of temperature and pressure on equilibrium composition. The experimental data is from the wood slurry runs on 4/12/02 and 4/17/02 is indicated by symbols. These runs were carried out at 3400 psi at 650°C and 800°C (nominal highest gasifier temperature), respectively. To obtain the equilibrium curves, the feed composition for the experimental runs was expressed as an equivalent composition of H_2O, H_2, and CO_2, and the equilibrium composition was calculated at various temperatures and pressures. There can be significant temperature changes as the gas mixture composition equilibrates - the temperature coordinate for the calculations is the final equilibrium temperature. For each gas species calculations were carried out at 5 pressures – 30, 500, 1500, 3400, and 4000 psia. The arrows for each species indicate the direction of increasing pressure. Any single Stanjan equilibrium calculation is carried out at constant pressure and enthalpy, and includes only the species water, hydrogen, methane, carbon monoxide and carbon dioxide – there is essentially no free oxygen remaining at equilibrium conditions.

The equilibrium calculations represent a simplified, idealized case, and we do not necessarily expect to attain the calculated composition. Nevertheless, the theoretical calculations do provide useful guidelines and trends for comparison. The measured gas composition data corresponds to the equilibrium calculations quite well at 650°C (Figure 2-12), but is significantly off at 800°C (Figure 2-13). This observation will be discussed further below. Carbon dioxide concentration is higher at 800°C due to the need to oxidize more feed to attain the higher gasifier temperature.

Figures 2-12 and 2-13 both show that higher pressures and lower temperatures generally favor methane as compared to hydrogen. This effect is not significant in terms of hydrogen end product; however, as the SWPO gasifier will be followed by a methane-steam reformer in a production plant.
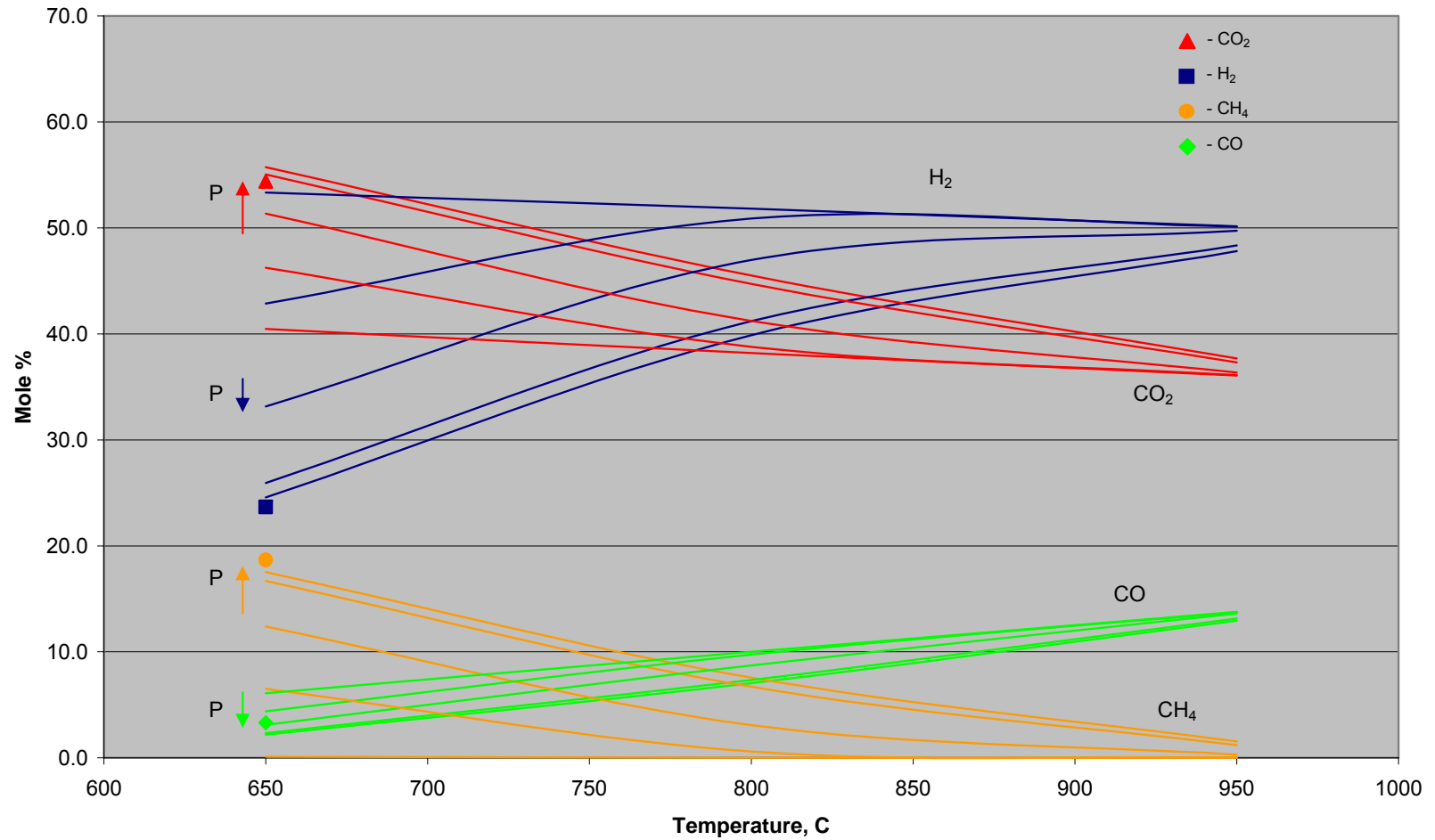
Figure 2-12. Comparison of GA results at 650°C with Stanjan equilibrium calculations.
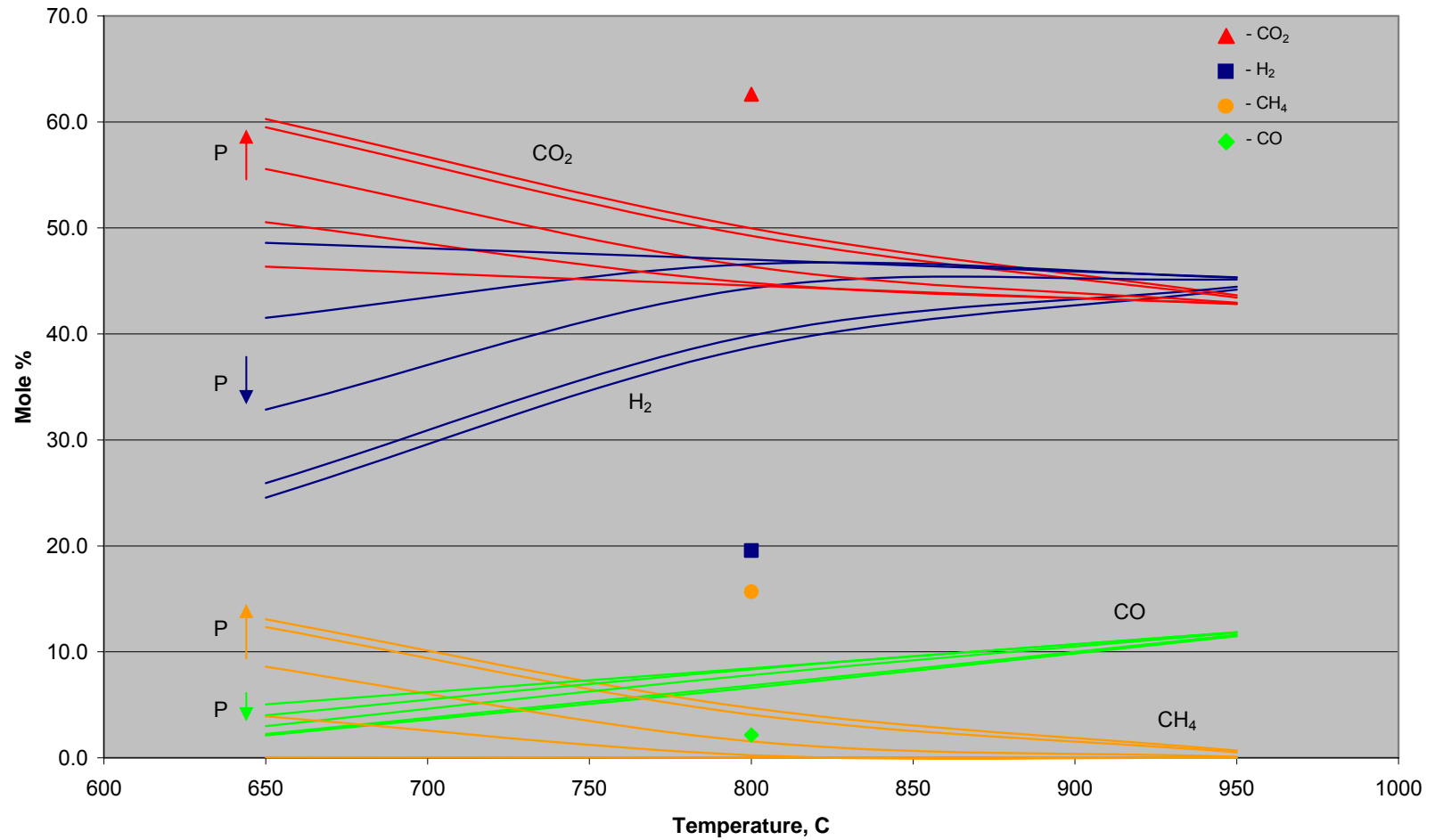
Figure 2-13. Comparison of GA results at 800°C with Stanjan equilibrium calculations.

Figure 2-14 presents a scatter plot comparing both GA results and UHM results to Stanjan equilibrium calculations. The figure shows the higher expected hydrogen yields in an indirectly heated gasifier (such as the UHM SCW gasifier), as compared to a directly heated gasifier (such as the GA SWPO gasifier), in which there is dilution of the gaseous products by carbon dioxide from the oxidation reaction. In addition to the dilution effect, the excess carbon dioxide in a directly heated gasifier is unfavorable to the methane-steam reforming reaction

$$CH_4 + 2H_2O \Leftrightarrow CO_2 + 4H_2 \qquad\qquad (1)$$
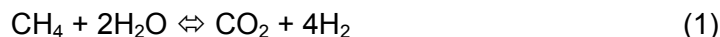
reducing the amount of hydrogen in the product gas. These are fundamental characteristics of the gasifier type. Schemes have been proposed to circumvent this problem by removing gas phase CO_2 from the system. For example, Lin et al. (1999a,b) and Wang and Takarada (2001) describe the use of lime for in-situ sequestration of CO_2 during supercritical water gasification of coal to improve gasification yields and reduce greenhouse gas emissions. This technique is another potential future improvement for SWPO.

As shown in Figure 2-14 (and as was seen in Figures 2-12 and 2-13), the GA results at 650°C tend to be close to equilibrium, while those at 800°C tend to deviate significantly. Furthermore, this trend was reproducible in that it held true for all 3 data points at each gasifier temperature. One reason the 800°C data points deviate from equilibrium is very likely insufficient time at temperature. Review of Figures 2-8 and 2-10 shows that there was considerably more temperature drop across the gasifier at 800°C as opposed to at 650°C. However, even the trend of the data in going from 650°C to 800°C in Figure 2-14 is sometimes wrong. For example, hydrogen content should increase at the higher temperature, but instead it decreases. The explanation for the peculiar behavior of the gas composition may have to do with erratic fuel/feed oxidation. As shown in Figure 2-10, gasifier temperatures were quite erratic at the higher temperature of operation, which was attributed to poor nozzle dispersion. It may be that the lower density reaction medium at 800°C was more susceptible to undispersed feed globules dropping through the gasifier, resulting in insufficient residence time and a poorer approach to equilibrium. Phase II tests with an improved nozzle design and gasifier internals to insure sufficient solids residence time should help answer this question.

It is important to note that equilibrium calculations pertain to composition of product gases and do not in any way reflect the yield attained or, more importantly, the economics of a process.

Comparison with Equilibrium

Figure 2-14. Comparison of GA and UHM results with Stanjan equilibrium calculations.
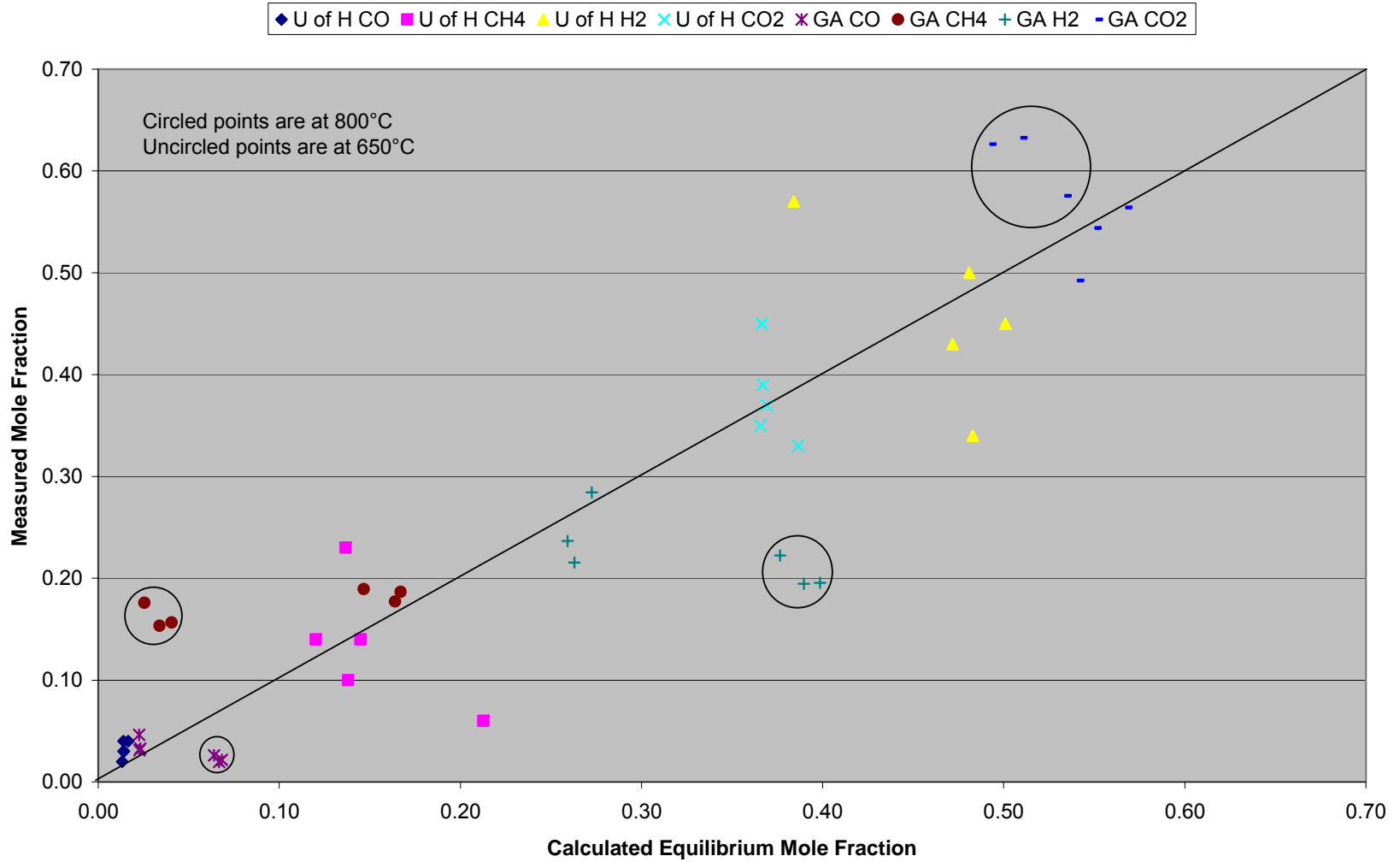
2.3.   COMPARISON OF SWPO WITH OTHER GASIFIERS

Tables 2-3 and 2-4 compare the results of the GA SWPO wood slurry tests in Table 2-2 with those of other gasifiers. Comparisons are given with both indirectly heated (Table 2-3) and directly heated or partial oxidation (Table 2-4) gasifiers. When comparing with indirectly heated gasifiers, only the unoxidized portion of the SWPO wood and ethanol is assumed to be available for gasifying when calculating the hydrogen yield, and the CO_2 produced by oxidation is deleted from the product gas composition. When comparing with directly heated gasifiers, all of the SWPO wood and ethanol are included in the yield calculations. In either case the product gas composition is corrected to be on an oxygen- and nitrogen-free basis. (See Table 2-2 for the SWPO product gas oxygen and nitrogen content.)

As seen in Tables 2-3 and 2-4, in comparison to other gasifiers, the supercritical water gasification processes of GA and UHM have significantly higher steam to carbon ratios due to their processing of relatively dilute slurries. The high water content encourages the carbon-steam gasification (2) and water gas shift (3) reactions:

$$C + H_2O \Leftrightarrow CO + H_2 \qquad\qquad\qquad (2)$$

$$CO + H_2O \Leftrightarrow CO_2 + H_2 \qquad\qquad\qquad (3)$$

The effect of reaction 3 is clearly seen in Tables 2-3 and 2-4 in terms of the low CO content in the product gas of the SCW processes. This may provide an economic advantage in eliminating the need for shift reactors downstream of the SWPO gasifier.

Tables 2-3 and 2-4 show the product gas composition for the various gasifiers. In conjunction with the feed composition and feed rate, and the product gas flow rate, the compositional data can be used to calculate a gasification efficiency. To start with, the feed composition and feed rate are used to calculate the maximum possible H_2 that could be formed, assuming that all feed carbon is converted to CO_2 and all oxygen is provided by water. For example, for cellulose the chemical equation is:

$$C_6H_{10}O_5 + 7H_2O \Leftrightarrow 6CO_2 + 12H_2 \qquad\qquad\qquad (4)$$
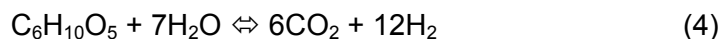
TABLE 2-3. COMPARISON OF SWPO GAS PRODUCTION WITH INDIRECTLY HEATED GASIFIERS

Organization	Feed	T °C	P psi	H_2O:C ratio	Product gas mol%					Max possible H_2 yield, g/100g feed		Max possible gasification efficiency, %	Notes
					H_2	CH_4	C_2+	CO	CO_2	Feed	Product gas		
GA	9% wood + 2.5% CMC[1]	650	3400	7.5	43.6	38.3	0.2	6.3	11.5	19.4	15.3	79	Yields based on unoxidized organic
GA	9% wood + 2.5% CMC[1]	650	3400	6.7	40.0	31.6	0.3	5.6	22.5	20.1	17.5	87	Yields based on unoxidized organic
GA	9% wood + 2.5% CMC[1]	800	3400	8.4	38.5	30.8	0.2	4.3	26.2	18.6	15.6	84	Yields based on unoxidized organic
GA	9% wood + 2.5% CMC[1]	800	3400	9.9	44.7	35.4	0.2	5.2	14.5	17.5	21.1	121	Yields based on unoxidized organic
GA	9% wood + 2.5% CMC[1]	650	3400	7.1	47.4	29.5	0.4	7.7	15.0	19.7	16.8	85	Yields based on unoxidized organic
GA	9% wood + 2.5% CMC[1]	800	3400	9.0	37.6	29.6	0.2	3.8	28.8	18.2	17.2	94	Yields based on unoxidized organic
UHM	10.4% CS[2]	650	4061	14.0	45	14	0.0	2	35	13.7	14.5	105	UHM, 1997a
UHM	5% wood + 5.5% CS[2]	650	4061	12.6	34	23	0.2	3	45	15.2	13.3	87	UHM, 1997a
UHM	5% wood + 5.6% CS[2]	650	4061	12.6	50	10	0.0	4	39	15.2	15.5	102	UHM, 1997a
UHM	5% wood + 6.1% CS[2]	650	4061	11.9	43	14	0.2	3	37	15.1	13.5	89	UHM, 1997a
UHM	11.5% wood + 4.2% CS[2]	650	4061	7.6	57	6	0.0	4	33	15.9	15.2	95	UHM, 1997b
TNO	Waste biomass	600	4351	NA	54	9	NA	3	34	NA	NA	NA	TNO, 1998
Battelle	Wood	826	25	0.8	21	16	5.8	43	13	18.0	12.5	70	Craig and Mann, 1996
Battelle	Wood	927	15	0.6	21	15	6.0	47	11	18.5	13.2	72	Katofsky, 1993
Wright-Malta	Wood	600	218	1.1	21	35	0.0	7	38	17.2	17.3	101	Katofsky, 1993
MTCI	Wood	697	15	2.6	50	8	0.4	22	19	17.8	14.9	84	Katofsky, 1993

Notes:
1. CMC is carboxymethylcellulose suspension agent.
2. Activated carbon catalyst. CS is corn starch.

TABLE 2-4. COMPARISON OF SWPO GAS PRODUCTION WITH DIRECTLY HEATED GASIFIERS

Organization	Feed	T °C	P psi	H₂O:C ratio	O₂:Feed mass ratio	Product gas mol%					Max possible H₂ yield, g/100g feed		Max possible gasification efficiency, %	Notes
						H_2	CH_4	C_2+	CO	CO_2	Feed	Product gas		
GA	9% wood + 2.5% CMC[1,2]	650	3400	3.9	1.0	21.5	18.9	0.1	3.1	56.3	21.9	8.1	37	Yields based on all organic
GA	9% wood + 2.5% CMC[1,2]	650	3400	3.6	0.9	23.6	18.6	0.2	3.3	54.3	21.9	9.7	44	Yields based on all organic
GA	9% wood + 2.5% CMC[1,2]	800	3400	4.0	1.1	19.5	15.6	0.1	2.2	62.5	22.0	7.7	35	Yields based on all organic
GA	9% wood + 2.5% CMC[1,2]	800	3400	4.1	1.2	22.2	17.6	0.1	2.6	57.5	22.2	9.3	42	Yields based on all organic
GA	9% wood + 2.5% CMC[1,2]	650	3400	4.0	0.9	28.4	17.7	0.2	4.6	49.1	21.6	9.7	45	Yields based on all organic
GA	9% wood + 2.5% CMC[1,2]	800	3400	4.0	1.1	19.4	15.3	0.1	2.0	63.2	22.1	8.0	36	Yields based on all organic
IGT	Wood, air-blown[3]	830	460	0.7	0.3	25	18	0.2	19	38	17.3	10.6	62	Craig and Mann, 1996
IGT	Wood, O₂-blown	982	500	0.7	0.3	31	12	0.5	22	35	17.0	11.6	68	Katofsky, 1993
TPS	Wood, air-blown[3]	870	20	0.3	0.5	37	0	0	46	16	17.3	11.1	64	Craig and Mann, 1996
Shell-bio	Wood O₂-blown	1085	352	0.2	0.5	38	0	0	48	14	17.0	11.1	65	Katofsky, 1993

Notes:
1. CMC is carboxymethylcellulose suspension agent.
2. Nitrogen- and oxygen-free basis used for product gas (see Table 2 for full composition).
3. Nitrogen-free basis used for product gas.

The maximum possible H_2 yield of the feed is expressed in terms of grams of hydrogen per 100 grams of dry (water-free) feed. The maximum possible hydrogen yield for cellulose is thus 24/162, or 14.8 g per 100 g of dry feed. The maximum possible hydrogen yield varies depending on the feed composition; some examples are given in Table 2-5. The table includes values for ethanol and wood, which are of particular relevance for the Phase I work, and SSS and trap grease, which are of particular relevance for the Phase II work. The organic portion of SSS actually has more potential for hydrogen production than does wood, but the high ash content of SSS reduces its potential on an overall basis. Trap grease, a favored fuel for Phase II and further development, has more potential for hydrogen production than does ethanol, the fuel used for Phase I testing. In general, the higher the heating value of a feed, the higher the maximum possible hydrogen yield.

TABLE 2-5. MAXIMUM POSSIBLE GASEOUS HYDROGEN YIELD

Material	Formula	Max g H_2 per 100 g dry feed	Reference
Polyethylene	CH_2	42.9	
Trap grease	$CH_{1.89}O_{0.13}$	35.2	Czernik et al., 2002
Ethanol	C_2H_6O	26.1	
GA Wood	$CH_{1.26}O_{0.62}$	17.3	GA Phase I testing
UHM Wood	$CH_{1.46}O_{0.68}$	16.7	UHM, 1997a
Mixed undigested SSS	$CH_{1.71}O_{0.48}N_{0.1}$, 28% ash	15.1	European Commission, 2001
Cellulose	$C_6H_{10}O_5$	14.8	
Corn starch	$C_6H_{11.4}O_{5.7}$	13.7	UHM, 1997a
Mixed digested SSS	$CH_{1.84}O_{0.53}N_{0.1}$, 50% ash	10.1	European Commission, 2001

In the next step to calculate gasification efficiency, the product gas composition and flow rate are used to calculate the maximum possible H_2 that could be formed from the product gas, again expressed as grams of hydrogen per 100 grams of dry (water-free) feed. (To actually achieve the maximum possible H_2 from the product gas, all the CH_4 would have to be reformed to H_2 and CO by reaction 1 and all the CO would have to be converted to H_2 and CO_2 by reaction 3.) Comparison of the maximum possible yield from the product gas with the maximum possible yield from the feed results in the maximum possible gasification efficiency shown in the next to last columns of Tables 2-3 and 2-4. In actual practice, gasification yields will be somewhat lower.

For the indirectly heated gasifiers of Table 2-3, the maximum possible GA gasification efficiencies range from 79% to 94% (discounting the point that gives 121% efficiency), slightly lower than those for UHM that range from 87% to near 100%. The carbon catalyst utilized by UHM may be responsible for the higher yields, but it is also possible that some of the catalyst itself was gasifying and artificially inflating yields. Note that UHM attributed a substantial catalytic effect to the wall of the nickel alloy tubular gasifier, an effect that would diminish for larger gasifiers such as GA's. The Wright-Malta gasifier also gives about 100% gasification efficiency, but the SCW gasifiers compare favorably to the Battelle and MTCI gasifiers. SWPO

gasification efficiency is expected to increase with Phase II and future developments. An improved feed injection nozzle should substantially reduce tar and char formation, and an increased solid particle residence time should further reduce residual tar and char resulting in higher gasification yields. It should be noted that even for the initial results of the Phase I SWPO testing, the maximum possible product gas H_2 yields already compare very favorably with the other gasifiers. This is a result of the ability of SWPO to take advantage of wet, dirty feedstocks such as grease trap waste (simulated by ethanol in Tables 2-3 and 2-4).

In comparison to the directly heated gasifiers of Table 2-4, the GA gasification efficiencies average about 40% while the gasification efficiencies for the IGT, TPS and Shell gasifiers average about 65%. The primary reason for the lower GA gasification efficiency is the processing of a relatively dilute feed stream, combined with the limitation on heat recycle in that the feed slurry was only preheated to 250°C. The high water to carbon ratio and the low degree of preheat required oxidation of a relatively large amount of fuel to reach the desired gasification temperature, reducing the maximum possible hydrogen yield of the product gas stream. The relatively large proportion of feedstock oxidation required is reflected in the high oxygen to feed ratio shown for SWPO in Table 2-4. GA anticipates that significant gains in gasification efficiency will be attained as SWPO is further developed. As mentioned previously for example, an improved feed injection nozzle should substantially reduce tar and char formation, and an increased solid particle residence time should further reduce residual tar and char resulting in higher gasification yields. In addition, higher feedstock slurry concentrations appear to be attainable with some development. As will be later discussed, there are also indications that significantly higher preheat temperatures are possible with some feeds. Similar to the indirect gasifier comparison, even for the initial results of the Phase I SWPO testing, the maximum possible product gas H_2 yields are already approaching those of the conventional gasifiers.

While Tables 2-3 and 2-4 are useful in comparing the product gases and gasification efficiencies from the different gasification processes, they say little about the over-riding issue of economics. For example, when operating on woody biomass all of the gasifiers in Tables 2-3 and 2-4 require feedstock preparation. The non-SCW gasifiers typically require both feedstock size reduction and drying. In the extreme, work has been done to essentially covert cellulosic biomass to a coal-like material to allow feeding to a conventional gasifier (Wallman et al., 1996). The SCW gasifiers do not require feed drying, but may require a finer feed size. Feedstock preparation costs can have a significant effect on the process economics. Minimal feed preparation is required for SSS and grease trap wastes.

Another example of economic factors not reflected in Tables 2-3 and 2-4 is system and equipment design for the different processes. The Wright-Malta gasifier, which shows excellent gasification yields in Table 2-3, is a rotary kiln device that requires about 1 hour of residence time. In contrast, the other gasifiers have residence time requirements of only minutes or seconds. The SCW gasifiers are extremely compact reactors operating at elevated pressure, with relatively small capital costs.

Section 5.1 will present an economic analysis of the SWPO process using the gasification yields obtained during the Phase I testing, which can only be expected to improve. Even given these conservatively low yields, by taking advantage of the particular capabilities of SWPO, economic production of hydrogen by avenues not available to the other technologies is enabled. Key SWPO features utilized in the economic analysis are:

- Ability of SWPO to process wet, dirty, negative value feedstocks

- No catalyst necessary, no concerns for bed blockage or catalyst fouling

- Low sulfur content of product gas due to inherent scrubbing action

- Production of low pressure steam

- Residence time of 1 minute or less

SWPO features that are not utilized in the economic analysis, but which may prove advantageous with further development of an optimized SWPO system include the following:

- Production of high pressure hydrogen

- Methane reforming without cooling and reheating the SWPO gasifier product gas

- Production of high pressure steam

- High pressure favors CO_2 capture and sequestration

3. TASK 2: PILOT-SCALE DESIGN & ANALYSIS

Phase I testing identified a number of areas where design improvement might be possible. Most of these areas of improvement were discussed earlier in Section 3. These areas are discussed further below.

Slurry pumping

The dual syringe slurry pump was able to provide reliable pumping of thick slurries. At this point what is needed is long-term testing to demonstrate reliability, especially with the newly defined target feedstocks such as sewage sludge plus grease trap waste or biomass/plastic slurries. In the latter case, there is already some related long-term data. Slurries of sawdust mixed with ground plastic and rubber have been successfully pumped and fed to a SCWO reactor in thousands of hours of testing carried out for the U.S. Army. Slurries containing ground activated carbon have also been processed for hundreds of hours.

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Feed Heatup

As discussed earlier, we were unable to achieve reliable preheat of slurry feeds above about 250°C due to preheater plugging. This is consistent with previous GA experience with mixed wood/plastic/ rubber slurries in work carried out for the U.S. Army. Some of the difficulties experienced, however, may be due to the design of the heat exchanger as opposed to inherent properties of the slurries. At a typical feed rate of 350 g/min, the velocity in the heat exchanger was about 0.1 m/sec. The Durand equation may be applied (Perry and Green, 1997) to determine if this velocity is sufficient to keep the wood particles entrained in the liquid flow. The Durand equation is:

$$V_{M2} = F_L[2gD(s-1)]^{0.5} \qquad\qquad (5)$$

Where V_{M2} is the minimum velocity for complete suspension, F_L is an empirical function of the particle diameter and the solid volume fraction of the feed, g is the acceleration due to gravity, D is the particle diameter, and s is the ratio of solid to liquid density. Substituting in this equation for the maximum particle size of about 1 mm and using a water-saturated wood density of 1.1, the velocity is marginally sufficient to keep the particles suspended at the preheater inlet, but insufficient as the slurry heats up past 170°C and drops in density. Furthermore, solids agglomeration may occur in the preheater and exacerbate any tendency toward settling.

The preheat heat exchanger incorporated in the GA pilot plant was designed to handle flowrates of at least 1 kg/min and preheat temperatures of 400°C and higher. It is comprised of 12 straight legs, each with a length of about 6 meters. Thus, for the wood slurry tests the total residence time in the preheat exchanger was about 12 minutes. At the throughputs used, heatup of the feed required only a single leg of the heat exchanger – in the other 11 legs the temperature was essentially constant at 250°C. This long residence time in the subcritical

region may have contributed to char formation. Furthermore, the preheat exchanger was of a design that incorporated tight, welded hairpin turns for compactness. These tight turns may have served as accumulation points for char and ash, making the exchanger prone to plugging and difficult to inspect and clean. Effort will be devoted to this area in Phase II, as the preheat temperature has a significant effect on the process efficiency and economics. A straight, smaller diameter heat exchanger is planned that can be readily inspected and rodded out.

As will be subsequently described, there are several indications from the literature and from GA's prior experience that sewage sludge can be preheated significantly above 250°C. Thus, preheat may be another factor making sewage sludge an ideal target feed.

Gasifier Design

Phase I testing was carried out in the absence of catalyst. Prior GA (1997) and UHM (1998a and b) SCWG studies used a packed bed catalyst. Use of a catalyst introduces problems of catalyst durability, poisoning, and bed plugging and handling. The Phase I results do not support the need for a catalyst – as was seen in Figure 2-14, GA's results at 650°C were as close to equilibrium as were the UHM results and as seen in Table 2-3, gasification efficiency was similar to UHM. Efficient gasification without catalysis is seen as a major advantage for SWPO.

Figures 2-12 through 2-14 showed significant quantities of methane at equilibrium in the SWPO gasifier. To improve hydrogen yields, a conventional catalytic methane-steam reformer can be used downstream of the SWPO gasifier. Use of a reformer should be facilitated by the clean gas product from the SWPO gasifier, which has been efficiently scrubbed during the cooldown and condensation of the SWPO gasifier effluent.

As discussed earlier, one area of potential improvement is in the design of the feed injector nozzle. In the Phase I tests, a relatively large nozzle orifice of 0.180-in. diameter was used to minimize the chance of nozzle plugging for a variety of feedstocks. This nozzle size gives a low velocity feed jet and relatively poor mixing. Based on thousands of hours of SCWO testing carried out for the U.S. Army at similar flow rates with slurries of sawdust mixed with ground plastic and rubber, use of a 0.070-in. nozzle should give better performance. For this size nozzle, particle size should be less than 1 mm diameter. Sewage sludge of 1 mm maximum diameter should likewise be amenable to this size nozzle. A nozzle of this type will be tested in Phase II.

Paragraphs deleted due to proprietary content.

Phase I testing provided some key guidelines for the next step in development of the SWPO technology. These guidelines are summarized below:

1. Pumping tests indicate that a slurry feed concentration of about 12 wt% biomass solids is a conservative maximum. Composted municipal solid waste mixed with sewage sludge solids was pumped at about 30 wt% during Phase I, and other observations suggest that 14 wt% sawdust slurries should be pumpable. GA has previously had good success at pumping sewage sludge at solids contents of 10-14 wt%, while literature sources claim that 15 wt% is pumpable. Economic projections utilizing 12 wt% thus represent a conservative minimum. If higher concentrations can be pumped, as appears likely, SWPO economics will be improved.

2. Feed preheat should be limited to 260°C to avoid char formation and plugging. Higher preheat temperatures may be possible with certain feedstocks or with improved heat exchanger designs, but these have not yet been demonstrated by GA.

3. Due to the limitations on feed slurry biomass concentration and feed preheat temperature, a high heating value waste must be coprocessed with the biomass in order to attain the desired gasifier temperature and still have sufficient feedstock for gasification. This is essentially the approach that evolved during Phase I testing, although the high heating value feed was the model compound ethanol as opposed to a waste material. Suitable high-heating value wastes are plastics, rubber, or trap grease.

4. Use a vessel-type gasifier as opposed to a pipe-type gasifier to allow higher gasifier operating temperatures and heat conservation.

5. Use a catalyst-free gasifier to enable long-term operation with dirty feed materials without plugging.

6. Use a high-energy nozzle giving high dispersion of the incoming feed to improve mixing and attain high gasification yields.

7. Use a methane-steam reformer on the clean SWPO product gas.

In keeping with the preceding guidelines, Figure 3-1 provides a process flow diagram (PFD) envisioned for the next phase of SWPO development. Feed to the system is comprised of two waste streams, a thick aqueous biomass slurry and a high heating value auxiliary fuel or slurry. For biomass slurries primary candidates are sewage sludge, manure sludge, and shredded sorted municipal solid waste (MSW) slurries. For the high heating value stream primary candidates are trap grease, plastic or rubber slurries, and coal or coke slurries. The easiest market entry may well be for the use of 12 wt% sewage sludge in conjunction with trap grease,

as both of these wastes are ubiquitous and have reasonably well-defined negative value (i.e., the process will receive a well-defined credit for processing these streams). Additionally, waste grease is frequently recovered at municipal wastewater treatment plants where it is already contaminated with sewage (Wiltsee, 1998).

Referring to Figure 3-1, thick aqueous slurry is supplied to the system at high pressure via dual syringe pumps. Pressurized biomass slurry (or water during startup and shutdown) is fed to the preheater where it is preheated to a temperature of 260°C, or other suitable temperature depending on established limits for a particular feed material. High-pressure high heating value material, referred to for convenience as auxiliary fuel, is simultaneously supplied to the gasifier. The fuel may be supplied by a separate pump as shown in Figure 3-1, or alternatively mixed in with the thick biomass slurry. In the case of trap grease, for example, the material as collected from restaurants contains a substantial fraction of water. The grease may be dewatered, heated, and pumped into the system as shown in Figure 3-1, or mixed in dilute form directly with dewatered sludge solids. Oxygen is combined with the preheated slurry and auxiliary fuel at the gasifier inlet. Partial oxidation of some of the organics results in a nominal gasifier temperature of 650-800°C. The gasifier operates at 3400 psi. In the gasifier, the feed is converted primarily to CO_2, H_2O, H_2, CH_4 and CO.

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Figure 3-1. Process flow diagram for SWPO of sewage sludge with trap grease.

3-5
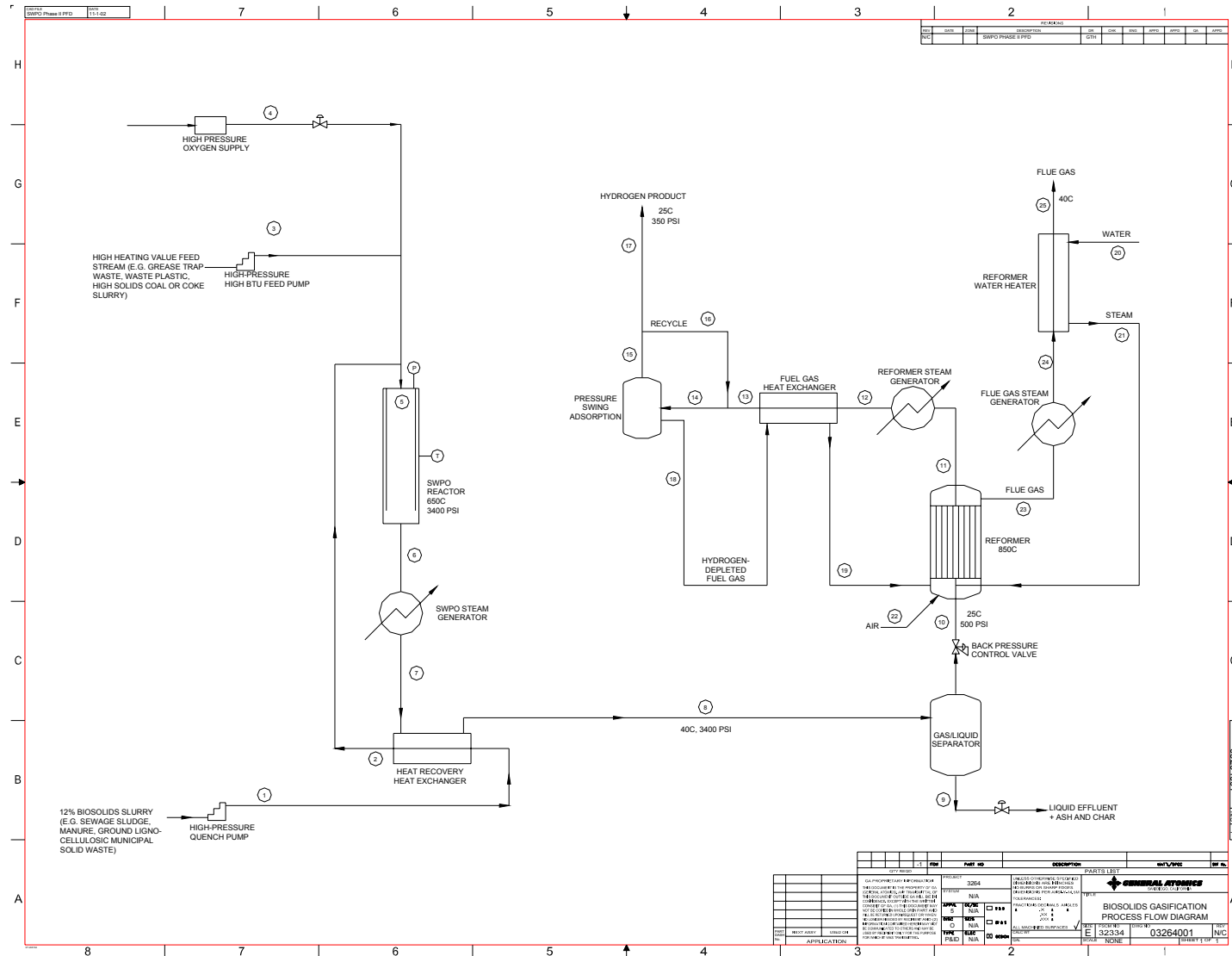
The gasifier effluent is cooled to near ambient temperature by a series of heat exchangers, in the process generating steam and preheating the incoming feed slurry. The condensation of liquid in the gasifier effluent is a highly efficient scrubbing mechanism, partitioning salts, particulates, and other water-soluble materials such as H_2S into the liquid phase. Next, the cooled gasifier effluent is phase separated in a high pressure gas-liquid separator. Condensed liquid with dissolved material and suspended ash is removed from the bottom of the separator. The clean gas phase exits from the top of the separator and is reduced in pressure to about 500 psi. It then enters a steam reformer where methane and other light hydrocarbons will be converted to hydrogen. To enable the reforming, steam is added to the reforming gas at a steam:carbon ratio of 3:1. The catalytic reforming takes place at 850°C, with the necessary temperature achieved by burning the hydrogen-depleted process offgas with ambient air.

The reformer flue gas is used to generate steam as well as preheat the incoming reformer water. Similarly, the hot reformed gas is used to generate steam and preheat the incoming fuel gas. Hydrogen is separated from the cool reformed gas using pressure swing adsorption (PSA). PSA requires that the feed gas contain at least 70% hydrogen. To meet this requirement, a portion of the hydrogen product gas from the PSA is recycled to the PSA feed gas. The hydrogen-depleted gas from the PSA is subsequently used to fire the reformer. Note that some but not all of these features will be tested during Phase II.

A mass and energy balance was carried out for the production-scale SWPO flowsheet of Figure 3-1. Table 3-1 lists key assumptions pertaining to these calculations. Gasification yields have been taken from GA's Phase I results with sawdust slurries, and are applied only to the organic fraction of the feed. Actual gas yields for SWPO mixtures of sewage sludge and grease have not yet been measured.

Table 3-2 presents the production-scale SWPO mass and energy balance. These mass and energy balance results were used as input to the economic study, described in the next section.

With regard to sewage sludge processing, a substantial amount of prior relevant work has been carried out. UHM (1996b, 1997b) reported several laboratory results showing good gasification using activated carbon catalyst, although ash precipitation plugged the narrow gasifier inlet within 2 hours. These tests utilized sludge concentrations from 2.1 to 7.7% in corn starch pastes in an indirectly heated tubular gasifier. Temperature and pressure conditions were 600-650°C and 4100-5100 psi. UHM (1998a) later reports mixed gasification yields from sewage sludge, with some tests showing reasonable gasification and others showing poor yields and even apparent inhibition of gasification of the corn starch carrier. The reason for the widely varying results is not clear, but it was suggested that sulfur or heavy metals in some of the sludges may have poisoned catalytic sites on the gasifier wall. These results further support the non-catalytic approach advocated by GA.

TABLE 3-1. SWPO PRODUCTION-SCALE MASS AND ENERGY BALANCE ASSUMPTIONS

Description	Assumption	Reference
Plant size	30 tons/day organic sludge solids, 40 tpd total solids (non-grease)	Numerous POTWs of this size in the US and worldwide
Sewage sludge suspended solids content	12%	Phase I testing and prior GA experience
Sewage sludge ash content	25%	UHM, 1997b
Sludge preheat temperature	260°C	Phase I testing
Grease feed (wet, as collected)	22-47 tons/day	Mass and energy balance
Gasification yields	GA Phase I results	GA, 2002
Grease trap water content	75%	Darling International telecon
Grease heating value (water-free)	16393 Btu/lb	www.cgfa.org/news.htm
Heat loss	None assumed	

GA has reported on several pilot-scale tests with sewage sludge for a previous DOE contract (GA, 1997). Sludge concentrations of between 0.5 and 7.5% were tested. GA has pumped sewage sludge at concentrations up to 14% in other SCWO testing (GA, 1998). These feeds were thickened with a small amount of polymer, as opposed to the large amount of corn starch used in the UHM tests. Indirect heating up to the gasifier temperature of 300 to 660°C was used, with a gasifier pressure of 3400 psi. The longest run utilized an activated carbon catalyst in a downflow vessel gasifier. Feed was supplied to the system for a bit under 2 hours, at which point differential pressure was building across the catalyst bed, presumably due to char/ash accumulation, and a decision was made to terminate the run. Reasonably good hydrogen yields were obtained, with a product gas containing 25% H_2 as compared to 33% H_2 in the early UHM testing. It is important to note that the GA pilot-scale testing had far less catalytic surface area relative to the lab-scale test at UHM. Thus, the UHM suggestion that wall catalysis is important is questionable.

TABLE 3-2. SWPO PRODUCTION-SCALE MASS AND ENERGY BALANCE

Stream No.	1	2	3	4	5	6	7	8	9	10	11	12
Stream Name	Sludge Solids Feed	Preheated Sludge	High BTU Feed	Oxygen	Gasifier Feed	Gasifier Effluent	Partially Cooled Effluent	Cooled Effluent	Liquid + Solid Effluent	Medium Pressure Gas	Reformed Gas	Warm Reformed Gas
Temperature, °C	25	260	25	25	650	650	253	40	40	25	850	577
Pressure, bar	235	235	235	235	235	235	235	235	235	37	35	35
Mass flow, kg/sec	3.50	3.50	0.49	0.72	4.71	4.71	4.71	4.71	3.36	1.35	3.32	3.32
Heat flow, MW	0.0	3.301	0.000	0.000	0.000	0.000	-8.916	-3.305	0.000	0.000	0.000	-1.582
Solids, kg/sec	0.42	0.42	0.00	0.00	0.42	0.11	0.11	0.11	0.11	0.00	0.00	0.00
Grease, kg/sec	0.00	0.00	0.49	0.00	0.49	0.00	0.00	0.00	0.00	0.00	0.00	0.00
O_2, kg/sec	0.00	0.00	0.00	0.72	0.72	0.00	0.00	0.00	0.00	0.00	0.00	0.00
H_2O, kg/sec	3.08	3.08	0.00	0.00	3.08	3.26	3.26	3.26	3.26	0.00	1.85	1.85
H_2, kg/sec	0.000	0.000	0.000	0.000	0.000	0.023	0.023	0.023	0.000	0.023	0.057	0.057
CO, kg/sec	0.00	0.00	0.00	0.00	0.00	0.04	0.04	0.04	0.00	0.04	0.13	0.13
CO_2, kg/sec	0.00	0.00	0.00	0.00	0.00	1.14	1.14	1.14	0.00	1.14	1.22	1.22
CH_4, kg/sec	0.00	0.00	0.00	0.00	0.00	0.14	0.14	0.14	0.00	0.14	0.06	0.06
N_2, 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

TABLE 3-2. SWPO PRODUCTION-SCALE MASS AND ENERGY BALANCE (CONT'D)

Stream No.	13	14	15	16	17	18	19	20	21	22	23	24	25
Stream Name	Cooled Reformed Gas	Reformed Gas w/ Recycle	PSA Product	PSA Recycle	Storage H2	PSA Fuel Gas	Heated PSA Fuel Gas	Reformer Cold Water	Reformer Heated Water	Combustion Air	Hot Flue Gas	Warm Flue Gas	Cold Flue Gas
Temperature, °C	25	25	25	25	25	25	569	25	249	25	850	100	40
Pressure, bar	35	35	35	35	35	1	1	37	37	1	1	1	1
Mass flow, kg/sec	3.32	3.44	0.14	0.11	0.02	3.30	3.30	1.97	1.97	4.53	7.83	7.83	7.83
Heat flow, MW	-7.317	0.000	0.000	0.000	0.000	0.000	7.319	0.0	5.3	0.0	0.0	-7.5	-6.1
Solids, 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
Grease, 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
O2, kg/sec	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.05	0.45	0.45	0.45
H2O, kg/sec	1.85	1.85	0.00	0.00	0.00	1.85	1.85	1.97	1.97	0.00	2.30	2.30	2.30
H2, kg/sec	0.057	0.170	0.136	0.113	0.023	0.034	0.034	0.00	0.00	0.00	0.00	0.00	0.00
CO, kg/sec	0.13	0.13	0.00	0.00	0.00	0.13	0.13	0.00	0.00	0.00	0.00	0.00	0.00
CO2, kg/sec	1.22	1.22	0.00	0.00	0.00	1.22	1.22	0.00	0.00	0.00	1.61	1.61	1.61
CH4, kg/sec	0.06	0.06	0.00	0.00	0.00	0.06	0.06	0.00	0.00	0.00	0.00	0.00	0.00
N2, kg/sec	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.47	3.47	3.47	3.47

A number of relevant sewage sludge SCWO demonstration efforts have been underway in recent years. These studies emphasize the perceived importance of the sewage sludge market for SCW processes. HydroProcessing, LLC (HP) has processed polymer-thickened sewage sludge in the range of 7% sludge solids for hundreds of hours in a full-scale plant in an attempt to commercialize this application of the SCWO process. The HP plant, located in Harlingen, Texas, is comprised of two identical trains each processing 5 tpd of dry sludge solids. The system operates at 3800 psi. The maximum sludge preheat temperature is about 350°C (Griffith, et al., 1999), while the maximum reactor temperature is about 600°C (Griffith, 2000). Some solids accumulation also occurred in the heat exchangers and reactor, which required occasional flushes with dilute nitric acid (Wofford, 2002).

Chematur Engineering AB of Sweden is also actively pursuing SCWO of sewage sludge. They have reported on a 30-hr test carried out in their pilot plant and sponsored by BOC and a consortium of 6 UK water companies (Patterson et al., 2001). For this test both 15% raw sewage sludge and 15% digested sewage sludge were produced from dilute sludges by centrifugation without the addition of polymer. Both feeds were processed at 230 kg/hr with no apparent problems. The sludges were preheated to 400°C and the final reactor temperature was about 600°C, with an operating pressure of about 3400 psi. A 100-hr test of sewage sludge was scheduled for late 2001 but no literature references have yet appeared. A Japanese licensee of Chematur, Shinko Pantec, has built a full-scale system for SCWO treatment of sewage sludge in Kobe, but again no further information is available in the literature.

Several of the preceding references pertain to SCWO as opposed to SWPO. The SCWO references nevertheless entail the same high-pressure pumping and feed preheating operations as does SWPO, and involve many similar considerations in reactor/gasifier design and pressure letdown, for example. It is important to note the indications that sewage sludge can be reliably pumped at 15% solids, and that preheat temperatures of at least 400°C may be workable with this feed. The above pre-commercial and commercial SCWO activities suggest that a consensus is developing that SCWO of sewage sludge can be competitive with current sludge disposal practices. SWPO of sewage sludge should have economics even more favorable than SCWO. In addition to producing the valuable byproduct of hydrogen, SWPO uses far less oxygen than SCWO, which is the major operating cost of a SCWO plant.

4. TASK 3: DEVELOPMENT PLAN

This section is comprised firstly of an economic analysis based on the Phase I test results that demonstrates the economic viability of the SWPO process. Following the economic analysis, the technology development plan is described in terms of the subsequent program phases. Briefly, these are Phase II – Technology Development; Phase III – System Integration and Design; and Phase IV – Reduced-scale Demonstration of 5 tpd System. Commercialization of the technology would take place subsequent to Phase IV. The development plan is a work in progress that must be updated at the completion of each phase of development to incorporate the most recent information and to revise plans for future work. Finally, the development of a SWPO Business Plan is described. The Business Plan itself is included as Appendix C.

4.1. ECONOMIC ANALYSIS

Identification of economically viable applications for hydrogen production has been a pacing factor in the development of the hydrogen economy. For hydrogen production from biomass-type feedstocks, economic viability has been dependent upon low-cost feedstocks and the coproduction of other useful chemical materials such as adhesive constituents or activated carbon (Czernik et al., 1999; Evans et al., 2001). GA has identified an economically viable application for hydrogen production based on the ability of the SWPO process to handle dirty, high moisture municipal waste feedstocks. Specifically, by co-processing sewage sludge in combination with grease trap waste, SWPO can transform feedstocks with a high negative value into hydrogen at highly competitive rates. Besides hydrogen, the coproducts of the SWPO process are steam (for possible power generation), clean water, inert ash, and reduced environmental degradation from sludge and trap grease disposal.

Because of its generally high negative value, municipal sewage sludge is a key target feed for early implementations of SWPO technology. This feedstock is plentiful, sustainable, and an ever-increasing disposal problem for municipalities of all sizes. As previously discussed, GA has successful prior experience with gasification of this feed, and related work in the literature is generally encouraging. Phase I testing and prior GA work with sewage sludge, however, indicate that the process may be limited to slurries with less than 15% organic solids and preheating may be limited to only about 250°C. The Phase I tests showed that a high heating value waste can be co-processed as an auxiliary fuel in the SWPO unit to overcome these limitations. Waste grease is an ideal candidate for the high heating value waste, as it has a modest negative value and is readily available in municipalities in rough proportion to sewage sludge. This auxiliary fuel feedstock is also plentiful, sustainable, and a chronic disposal problem in cities across the country. An economic analysis has therefore been carried out for co-processing of sewage sludge and waste grease. As the analysis shows, this scenario produces hydrogen at highly competitive rates. Furthermore, due to the ability of SWPO to process virtually any wet, dirty waste, once a market foothold is established with sludge/grease, candidate biomass feedstocks may be expanded to include materials such as sorted municipal solid waste, animal manures, and agricultural byproducts that can be co-processed with other auxiliary fuel feedstocks such as shredded plastic and rubber and low grade coal or petroleum

coke. SWPO thus has the potential to become a major waste cleanup technology, converting urban wastes of all types into clean distributed energy and hydrogen.

Most municipalities within the U.S. generate both primary and secondary sludges during the treatment of sewage. The process schematic for the Encina Wastewater Authority plant, located in Carlsbad, CA, shown in Figure 4-1, 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. Bacteria break down organics present in the water (aerobic digestion), which then flows to a secondary sedimentation tank. The bacteria-rich sludge settling in this tank is called secondary sludge or activated sludge. Some of this activated sludge is recycled to the aeration step to stimulate continuous bacterial growth.

Mixed primary and secondary sludge is typically about 6 wt% solids, with the sludge solids containing approximately 25% nonvolatile material, primarily sand and clay. With conventional sewage sludge practices at municipal installations, the mixed sludge is sent through an anaerobic digester, where it is partially metabolized by bacteria, producing CH_4, CO_2, and other by-products. The combustible gases produced may then be collected and used to generate heat for the digestion tanks and buildings, and to fuel gas engines for power generation for use in the plant. Residual solids from the anaerobic digestion step are depleted of a portion of their organic matter, and thus have higher nonvolatile content in comparison to undigested sludge. Table 4-1 shows typical compositions for mixed sludge before and after digestion, 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 mixed or digested sewage sludge than for corn starch or woody biomass. Thus, higher yields of hydrogen should be possible from the organic portion of sewage sludge than from corn starch or woody biomass.
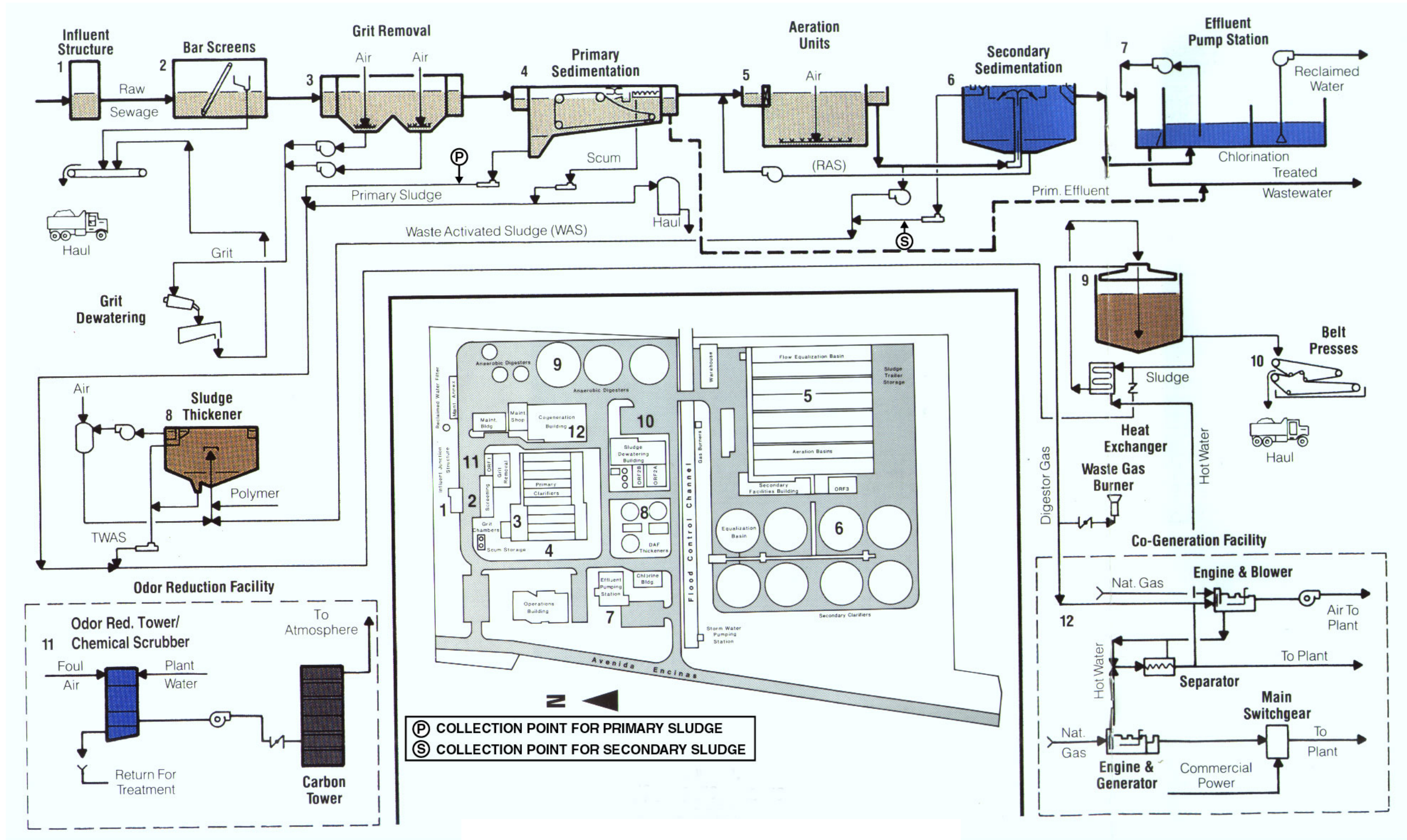
Figure 4-1. Encina Process Schematic and Site Plan

TABLE 4-1. TYPICAL COMPOSITION OF SOME BIOMASS MATERIALS

Element	Mixed Sewage Sludge[a]		Digested Sewage Sludge[a]		Corn Starch[b]		Woody Biomass[c]	
	Ash-Free Wt % (dry)	Mole ratio	Ash-Free Wt % (dry)	Mole ratio	Ash-Free Wt % (dry)	Mole ratio	Ash-Free Wt % (dry)	Mole ratio
Carbon	51.0	2.1	49.0	1.9	41.1	1	51.4	1.6
Hydrogen	7.4	3.6	7.7	3.5	6.5	2	6.1	2.3
Oxygen	33.0	1	35.0	1	52.4	1	42.3	1
Nitrogen	7.1	0.2	6.2	0.2	0	0	0.2	0.0
Sulfur	1.5	0.0	2.1	0.0	0	0	0.1	0.0
Nonvolatile wt%	28	-	50	-	0.0	-	0.9	-

References:

a - European Commission, 2001.

b - UHM, 1997b

c - Mann, 1995

Following volume reduction by anaerobic digestion, the treated sewage sludge is dewatered to about 30 wt% solids and this residue is now termed biosolids. (Some definitions of biosolids also require that the material is satisfactory for beneficial application to the land, e.g., sufficiently low in pathogens, metal content, etc.) The dewatered sludge solids may be disposed of by incineration, landfilling, or land amendment. Incineration is now the least favored means of disposal. Land filling and land amendment are currently in widespread use in the U.S., but costs continue to increase as environmental concerns increase.

As an alternative to conventional sludge digestion and disposal, undigested sludge from municipal wastewater treatment works can be treated via SWPO. SWPO can eliminate the need for anaerobic digestion and greatly reduce the quantity of residual material requiring further disposal, with a concomitant reduction in disposal costs. GA has demonstrated SCWG of 11% sewage sludge in a prior study for DOE (GA, 1997), as well as pumping of up to 14% sewage sludge derived solids (GA, 1998), and this work, together with the Phase I results, forms the basis for the economic analysis presented here.

As previously mentioned, waste grease is a good candidate for auxiliary fuel for the SWPO process. The primary sources of waste grease are grease traps at restaurants and food processing plants, and grease recovered at sewage treatment plants. Grease traps are used to prevent plugging of sewer pipes with solidified grease. The traps accumulate grease over time and must be regularly pumped out. In most locations in the U.S. this pumping is carried out by service companies that collect the grease, dewater it, and then dispose of the byproduct in a

landfill. The amount of trap grease generated per capita is about 13 lb/year (Wiltsee, 1998), which is about 20 to 25% of the amount of municipal sludge solids generated per capita.

Table 4-2 lists key assumptions pertaining to the SWPO commercial-scale economic analysis. SWPO gasification yields have been taken from GA's Phase I results for coprocessing sawdust slurries with ethanol auxiliary fuel. Actual SWPO gas yields for coprocessing mixtures of sewage sludge and grease have not been measured, but should be better than those obtained during Phase 1 because the organic portion of sewage sludge solids is less oxygenated than woody biomass, and grease has a higher H_2 formation potential than does ethanol (see Table 2-5). Gas yields should be further increased once the Phase II process improvements are made.

TABLE 4-2. SWPO ECONOMIC ANALYSIS ASSUMPTIONS

Description	Assumption	Reference
Plant size	40 tpd total solids, 30 tons/day organic sludge solids (not grease)	Numerous plants of this size in the US and worldwide
Sludge solids credit	$0-300 per dry ton	SDSU survey (Appendix D)
Gasifier residence time	20 seconds	15 seconds for UHM, 1998a
Trap grease credit	$0.08 per gallon	Darling/Al Max telecons
Steam credit	$3.50 per MMBtu (≈ 1000 lb)	Yeboah et al., 2002
Cost of liquid oxygen (LOX)	$0.04 per pound	Vendor discussions
Financing rate	6 to 12%	Current prime interest rate is below 5%
Financing period	Up to 20 years	City of San Diego methane contract is a 20-yr term

The credit for accepting sewage sludge varies considerably between municipalities. GA's recent survey of POTWs throughout the U.S. shows a range of disposal costs from about $50-500 per ton (see Appendix D). GA has identified the nearby Encina municipal wastewater treatment plant as a potential reduced-scale SWPO demonstration site. This plant currently serves a population of about 250,000 and in 1997 was paying $120 per dry ton to have their biosolids trucked away. They are currently paying $200 per dry ton and expect prices to continue to rise. The Encina site processes about 40 tpd of undigested sludge solids, the same size as the commercial-scale SWPO plant considered in the economic analysis. Numerous wastewater treatment plants the size of Encina exist across the US.

The grease trap credit of $0.08 per gallon is derived from discussions with Darling International and Al-Max Sanitation in San Diego, and are typical costs for medium to large metropolitan areas. The credit is based on avoided costs for grease solidification and disposal. Darling charges restaurants $0.15-0.25 per gallon to pick up their grease trap waste. The waste is 70-75% water. To separate and solidify the grease, lime and polymer are mixed in to yield a sand-like precipitate. This precipitate is then landfilled. Separation, solidification and landfilling of the grease costs about $0.06-0.10 per gallon of as-collected trap grease, including a landfill tipping fee of $42 per ton plus a "special waste" surcharge of $50 per truckload. This is equivalent to about $100/ton on a water-free basis. Darling collects about 15,000 gallons of trap grease per day, and has about 40% of the San Diego market. Our discussions with Al-Max Sanitation confirmed that a grease trap credit of $0.08 per gallon is reasonable. Al-Max stated that they would gladly pay $0.10 per gallon for someone to accept the grease trap waste.

A number of economic analyses were performed for different SWPO plant sizes, sludge solids/grease ratios, sludge solids credits, and financing rates. Tables 10 through 12 provide details on the analysis of the selected commercial-scale SWPO plant installed cost and operating costs. Table 4-3 provides the capital cost for the case of 40 tpd of slurried as-received sludge solids (30 tpd of organic sludge solids) coprocessed with trap grease. The ratio of grease to sludge is twice the amount necessary to raise the combined feeds to the final temperature of 650°C, and half of the grease or its equivalent is oxidized and the other half is gasified. This is the case covered by the mass and energy balance in Table 3-2, where it can be seen that the plant is processing about as much grease (0.49 kg/sec) as sludge solids (0.42 kg/sec). Table 4-4 shows the operating costs for this case while the plant capital expense is

TABLE 4-3. SWPO CAPITAL COST ESTIMATE FOR COMMERCIAL-SCALE PLANT

CAPITAL COSTS					
__Item__	__Size__	__Units__	__Size Basis__	__Cost__	__Cost Basis__
Biosolids storage tank	15979	gal	4 hours holdup + 25% head space	$34,298	Engineering estimate
Grinder/macerator	266	gpm	4x sludge pump	$114,343	Engineering estimate
Sludge pump	67	gpm	M&EB	$340,411	American Lewa quote, scaled by 0.6 power
Liquid oxygen (LOX) system	5726	lb/hr	M&EB	$189,986	Rickman 30 tpd estimate, 4/02
High Btu feed pump	9	gpm	M&EB	$99,858	American Lewa quote, scaled by 0.6 power
Heat recovery heat exchanger	11.3	MMBtu/hr	M&EB	$478,000	0.6 exponent scale from C. Hong quote
SWPO Gasifier (gasifier)	34	ft3	~20 sec residence time	$446,251	Rickman 30 tpd estimate, 4/02, scaled by 0.6 power
SWPO steam generator	30	MMBtu/hr	M&EB	$380,582	0.6 exponent scale from C. Hong quote
Gas/Liquid separator	516	gal	5 min liquid RT, 50% head space	$446,251	Rickman 30 tpd estimate, 4/02, scaled by 0.6 power
Reformer	4865	kg/hr	1995 Mann report	$63,954	1995 Mann report , scaled by 0.6 power
Reformer steam generator	5	MMBtu/hr	M&EB	$134,845	0.6 exponent scale from C. Hong quote
Fuel Gas heat exchanger	25	MMBtu/hr	M&EB	$29,976	1995 Mann report, direct scaling
Flue gas steam generator	28	MMBtu/hr	M&EB	$362,334	0.6 exponent scale from C. Hong quote
Reformer water heater	18	MMBtu/hr	M&EB	$23,702	1995 Mann report, direct scaling
3 boiler feedwater pumps	104	gpm	9, 46, 50 gpm	$208,356	Engineering estimate
PLC/control computer	-	-	System more complex than SCWO	$125,000	Rickman 30 tpd estimate, 4/02, x 1.25
Tanks, valves, fittings, instrumentation	-	-	System more complex than SCWO	$238,693	Rickman 30 tpd estimate, 4/02, scaled by 0.6 power

CAPITAL COSTS					
Item	**Size**	**Units**	**Size Basis**	**Cost**	**Cost Basis**
Skids	-	-	System more complex than SCWO	$103,779	Rickman 30 tpd estimate, 4/02, scaled by 0.6 power
Gas analyzers	-	-	H2, CO, CH4, CO2	$200,000	2x ROK
PSA module	856,416	scfd	M&EB	$213,180	1995 Mann report , scaled by 0.6 power
Total equipment				$4,233,800	
Design/engineering				$1,354,816	32% of equipment
Fabrication			System more complex than SCWO	$1,193,463	Rickman 30 tpd estimate, 4/02, scaled by 0.6 power
Facilities				$423,000	0.1 times major equipment cost
Startup			System more complex than SCWO	$460,000	Rickman 30 tpd estimate, 4/02, x 2
10% Contingency				$766,508	Rickman 30 tpd estimate, 4/02
15% Profit				$1,149,762	Rickman 30 tpd estimate, 4/02
TOTAL INSTALLED COSTS				$9,581,348	

TABLE 4-4. INITIAL SWPO OPERATING COST ESTIMATE FOR COMMERCIAL SCALE PLANT

OPERATING COST, $/YR @ 330 ANNUAL OPERATING DAYS				
<u>Item</u>	<u>Assumption</u>	<u>Units</u>	<u>Cost</u>	<u>Cost Basis</u>
Labor	6 operators		$350,000	Rickman 30 tpd estimate, 4/02
Oxygen	$0.04	per lb	$1,814,047	M&EB
Other utilities and chemicals, etc.	2	% of installed cost	$192,000	GA estimate
Maintenance	6	% of installed cost	$574,881	GA 30 tpd estimate, 4/02
Ash disposal	42	$/bone dry ton	$138,600	San Diego landfill
Capital recovery	20 years at 12% interest		$1,282,739	
Grease credit	$0.08	per gallon	$(1,228,292)	Credit = $20/wet ton @ 8 lb/gal
Steam credit	3.5	per MMBtu	$(1,593,080)	1200 psi steam if desired
Sludge solids credit	100	$/bone dry ton	$(1,320,000)	½ Encina disposal cost
TOTAL			$210,896	
Hydrogen kg/year	653365			
Hydrogen GJ/year	77358			
Hydrogen production cost, $/GJ	2.73			

TABLE 4-5. SWPO OPERATING COST ESTIMATE FOR COMMERCIAL SCALE PLANT FOLLOWING CAPITAL COST RECOVERY

OPERATING COST, $/YR @ 330 ANNUAL OPERATING DAYS				
Item	**Assumption**	**Units**	**Cost**	**Cost Basis**
Labor	6 operators		$350,000	Rickman 30 tpd estimate, 4/02
Oxygen	$0.04	per lb	$1,814,047	M&EB
Other utilities and chemicals, etc.	2	% of installed cost	$192,000	GA estimate
Maintenance	6	% of installed cost	$574,881	GA 30 tpd estimate, 4/02
Ash disposal	42	$/bone dry ton	$138,600	San Diego landfill
Capital recovery	Paid off		$0	
Grease credit	$0.08	per gallon	$(1,228,292)	Credit = $20/wet ton @ 8 lb/gal
Steam credit	3.5	per MMBtu	$(1,593,080)	1200 psi steam if desired
Sludge solids credit	0	$/bone dry ton	$0	
TOTAL			$248,157	
Hydrogen kg/year	653365			
Hydrogen GJ/year	77358			
Hydrogen production cost, $/GJ	3.21			

being recovered. Hydrogen production cost is highly competitive, at $2.73/GJ. Table 4-5 shows the operating costs for a case in which the plant capital expense has been paid off. In this case the SSS can be processed for free while retaining a highly competitive hydrogen production cost of $3.21/GJ. The detailed cost analysis in Tables 10-12 corresponds to a realistic commercial-scale plant size, with performance and financing parameters that can be applied to numerous sites throughout the U.S.

For a plant processing 40 tpd of sewage sludge solids, Figure 4-2 shows how the production cost (or alternatively, the required breakeven selling price) of the hydrogen produced varies with sludge solids credit, grease ratio, and plant financing. For the "1x grease" case the amount of grease supplied equals the amount necessary to raise the combined feeds to the final temperature of 650°C and all of the grease or its equivalent is completely oxidized to H_2O and CO_2. The "2x grease" case has twice this amount of grease, as mentioned above, and the "3x grease" case has three times this amount of grease. Financing rates of up to 12% have been used in view of the novel nature of the technology. The legend lists the financing rates in order of payment amount, i.e., 5 years at 12% requires the highest payment while 20 years at 6% requires the lowest payment. For each grease level, the rightmost lines correspond to the highest capital payments while the leftmost lines correspond to the lowest capital payments. It is important to note that the customers for these initial plants will be municipalities as opposed to commercial entities. Discussions with several municipalities suggest that very low financing rates may be possible, with long-term loan guarantees provided by the municipalities. Figure 4-2 shows that there is a significant subset of conditions under which hydrogen can have a highly competitive production cost (or breakeven selling price) of $5/GJ or less. Figure 4-3 shows how the hydrogen production cost or breakeven selling price is reduced once the capital cost is paid off. There is now only a single line for each grease level as the alternative financing terms are no longer relevant. For 3x grease, a hydrogen production cost of about $3/GJ can actually support a sludge solids payment to the supplier of about $75/bdt.

Ultimately, as distributed production of hydrogen becomes commercial, credits for sludge solids and grease may decrease and eventually become valuable waste products that can be sold at a profit. Thus, eventually, reduced credits or even payments for sludge and grease (rather than credits) may have to be offset by lower SWPO capital and operating costs.
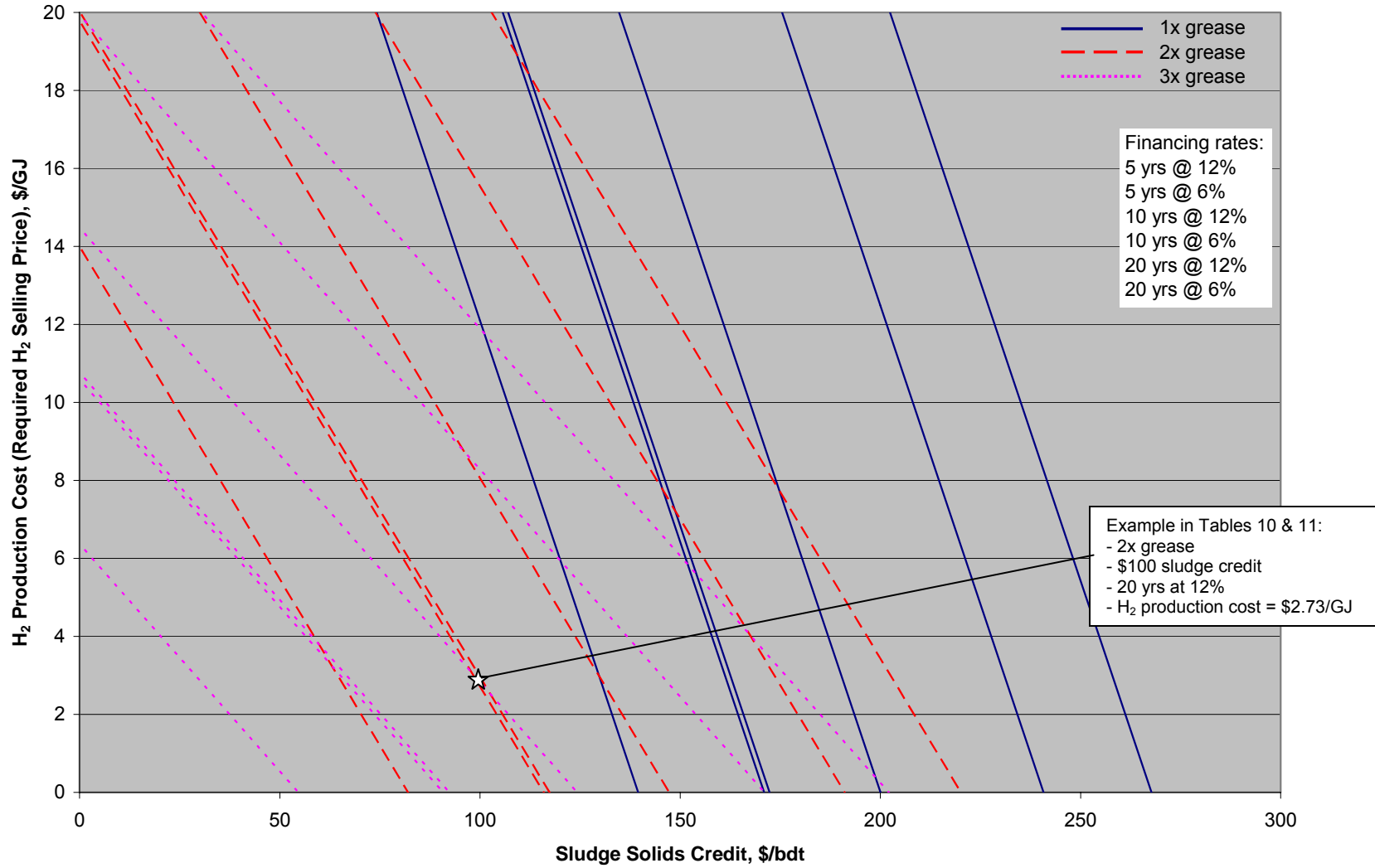
Figure 4-2. H$_2$ production cost for SWPO of 12 wt% sewage sludge coprocessed with grease auxiliary fuel.
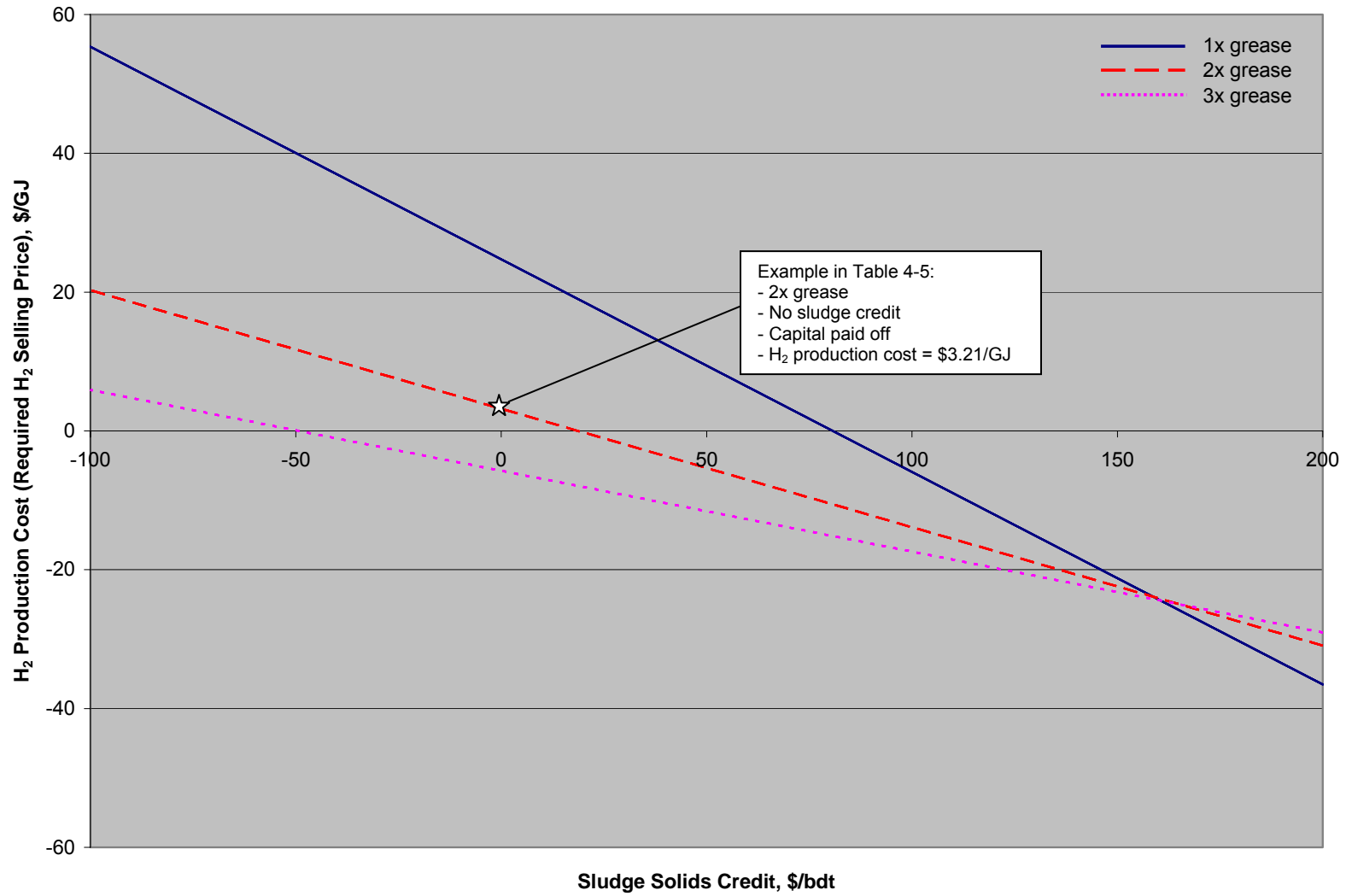
Figure 4-3. H_2 production cost for SWPO of 12 wt% sewage sludge coprocessed with grease auxiliary fuel following capital cost recovery.

- 1x grease
- 2x grease
- 3x grease

Y-axis: H_2 Production Cost (Required H_2 Selling Price), $/GJ

X-axis: Sludge Solids Credit, $/bdt

Example in Table 4-5:
- 2x grease
- No sludge credit
- Capital paid off
- H_2 production cost = $3.21/GJ

As SWPO distributed hydrogen production plants are installed at wastewater treatment plants, the sludge and grease credits may eventually decrease as the wastes begin to acquire value in the competitive marketplace. At this point, capital, operating and financing cost reductions, and/or alternative negative value feedstocks (manure, MSW) will be needed to maintain low hydrogen production costs. But by this time SWPO plants will be proven, and capital, operating and financing costs are expected to decrease sufficiently to offset the reduced sludge and grease credits.

While the economics of relatively small-scale SWPO hydrogen distributed production plants appear to be competitive with alternate hydrogen sources, a multi-phase development and demonstration program is needed before the technology is ready for commercialization. The following sections describe the Phase II through Phase IV development and demonstration activities.

4.2. PHASE II – TECHNOLOGY DEVELOPMENT: (1/03 – 12/04)

During Phase II, further development of SWPO technology will be performed to resolve knowledge gaps, and to define performance requirements and system interfaces for Phase III, System Integration and Design. The technical issues requiring further development were previously discussed in Sections 3 and 4. Testing of key SWPO subsystem components (e.g. feed mixing and pumping, feed preheating, feed injection and gasification, tar/char/ash handling, heat recovery, and pressure letdown) will be performed. This phase will involve longer duration tests than previously performed, with a target of 100 hours of continuous operation with the key target feed, sewage sludge plus grease trap waste, to demonstrate long-term operability. As part of the pilot test program, heat exchanger reliability will be monitored and measurements and observations regarding materials of construction will be carried out. Disposition and behavior of ash and char within the system will also be determined. As time and budget allow optional features (e.g. alternate feedstocks and a methane reformer) will be tested.

Task 1 – Develop Advanced SWPO Gasification System. Using the existing GA pilot plant, tests will be performed to demonstrate improved gasifier and heat exchanger designs and ability to handle the target sewage sludge feedstock coprocessed with grease trap waste. Time and budget permitting, tests will be performed with alternate feedstocks, alternate feed introduction schemes, and alternate gasifier designs. Specific subtasks are planned to:

1. Improve Pilot Plant instrumentation needed to improve mass balance and yield calculations.

2. Reduce residual char formation and improve gasification yields by improving mixing and increasing residence time at temperature.

3. Verify Phase I gasification yields with more representative feeds of 1) SSS + trap grease, 2) micronized wood + trap grease, and 3) SSS or micronized wood + micronized plastic or tire rubber.

4. Verify that the rate of char/ash buildup in the gasifier and heat-recovery heat exchanger and associated maintenance requirements are acceptable.

5.   *Deleted due to proprietary content.*

6.   *Deleted due to proprietary content.*

7.   Demonstrate a methane reformer integrated with the SWPO system (optional).

Task 2 – Systematize and Test Advanced SWPO Gasification System.

Once the installation of the advanced SWPO gasification system additions and modifications is complete, systemization of the integrated system will begin under Task 2. Systemization will consist of a step-wise startup and automation of the integrated system with representative feeds. Modifications to instrumentation and controls will be made as appropriate to assure robust, long-term operability.

Once systemization is complete, one or more long-term operability tests will be performed with representative feeds similar to those used in Task 1. Reliability and maintenance data will be recorded, along with the gasification data and system operating parameters. Test duration will be 50-100 hrs, with liquid and gas effluent samples taken at several intervals throughout the tests.

Task 3 - Perform Special Studies and Update SWPO Development Plan

In parallel with the Task 1 and 2 work, several studies will be performed to accumulate relevant technical and economic data for target SWPO feedstocks and other biomass-to-energy systems for comparison to the SWPO system.

1.   Feedstock Supply Assessment for Advanced SWPO Gasification Systems

A feedstock supply assessment will be performed to estimate the quantities and associated costs of selected biomass and auxiliary fuels that are available for the advanced SWPO gasification system, including sewage sludge (SS), sorted MSW such as wood, plastic and rubber, grease trap wastes, animal wastes, and potentially other (not yet identified) opportunity feeds. The focus will be primarily on feedstocks near metropolitan centers addressing supplies at various population densities.

2.   Preliminary Economic and Market Analyses for Advanced SWPO Gasification Systems

A preliminary economic analysis will be performed to evaluate the life cycle cost of the selected advanced SWPO hydrogen gasification system. The analysis will include estimates and forecasts of biomass and auxiliary fuel costs, system capital, operating and maintenance costs, potential credits, net hydrogen production costs over time and/or by-product revenue streams. A preliminary market analysis will be performed to better define the potential for deployment of advanced SWPO gasification systems. Initial deployment of SCWO systems for waste disposal will be assessed as an initial entry point into the municipal sludge market. National and regional markets may be considered, although emphasis will be placed on California as an ideal representative market for the proposed approach.

3.   Assessment of Biomass Gasifiers

A survey and assessment of biomass gasifiers will be performed to establish a comparative database for SWPO. The assessment will determine what gasifiers are currently or recently in

operation, and will tabulate key parameters, e.g. T, P, feedstock, steam/feed ratio, hydrogen production, char formation, etc. The purpose of the assessment is to assemble performance data in a consistent format that will allow comparative analysis of different gasifiers.

4. Assessment of Transportation-Grade Ethanol Life Cycle Cost

Transportation-grade ethanol has become a thriving business in recent years in the United States. The corn-to-ethanol life-cycle-cost (LCC) is useful as a comparative model for other feedstocks and processing methods. An assessment of the corn-to-ethanol LCC will be performed to identify common cost drivers for other feedstocks, and to define barriers to the development of biomass gasification and hydrogen production using SWPO.

5. Update of SWPO Development Plan

The results of these special studies will be used to update the SWPO development plan presented herein. The technical information from Tasks 1 and 2 will also be used in revising the development plan, and in defining the requirements for Phase III.

At the conclusion of Phase II, the SWPO PFD, M&EBs, and system interfaces (e.g., sewage sludge and grease trap waste supply, and separation, storage and disposition of H_2 product) will have been defined for the Phase III effort.

4.3.   PHASE III – SYSTEM INTEGRATION AND DESIGN: (1/05 – 12/05)

Phase III, System Integration and Design, involves detailed design and long-lead fabrication of dedicated equipment for the 5 tpd reduced-scale SWPO demonstration system for Phase IV, including industrial H_2 separation and storage systems. The piping and instrumentation diagram will be prepared and the process control logic developed. Equipment drawings and specifications will be prepared, long-lead equipment procured, and assembly begun. Supporting tasks, including a safety evaluation, RAM studies, and required permitting activities 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.

4.4.   PHASE IV – REDUCED-SCALE DEMONSTRATION SYSTEM: (1/06 – 12/08)

In Phase IV a 5 tpd reduced-scale version of the 40 tpd commercial-scale SWPO plant will be assembled, systemized, and then demonstrated. The reduced-scale unit will process about 5 tpd of sewage sludge solids, approximately one-eighth the size of the commercial-scale (40 tpd) for which viable economics have been projected. Figure 4-4 shows a conceptual layout of the 5 tpd system. The 5 tpd SWPO system will be based on an existing commercial SCWO system designed and built by GA. A likely site for the reduced-scale demonstration is the Encina wastewater treatment plant located near GA. In a visit to the Encina plant in October 2002, potential locations for an initial SWPO demonstration plant (about 5 tpd capacity) were discussed. Figure 4-5 shows the Encina sludge dewatering building, while Figure 4-6 shows one of the two interior locations that are potentially available in this building for the SWPO system.
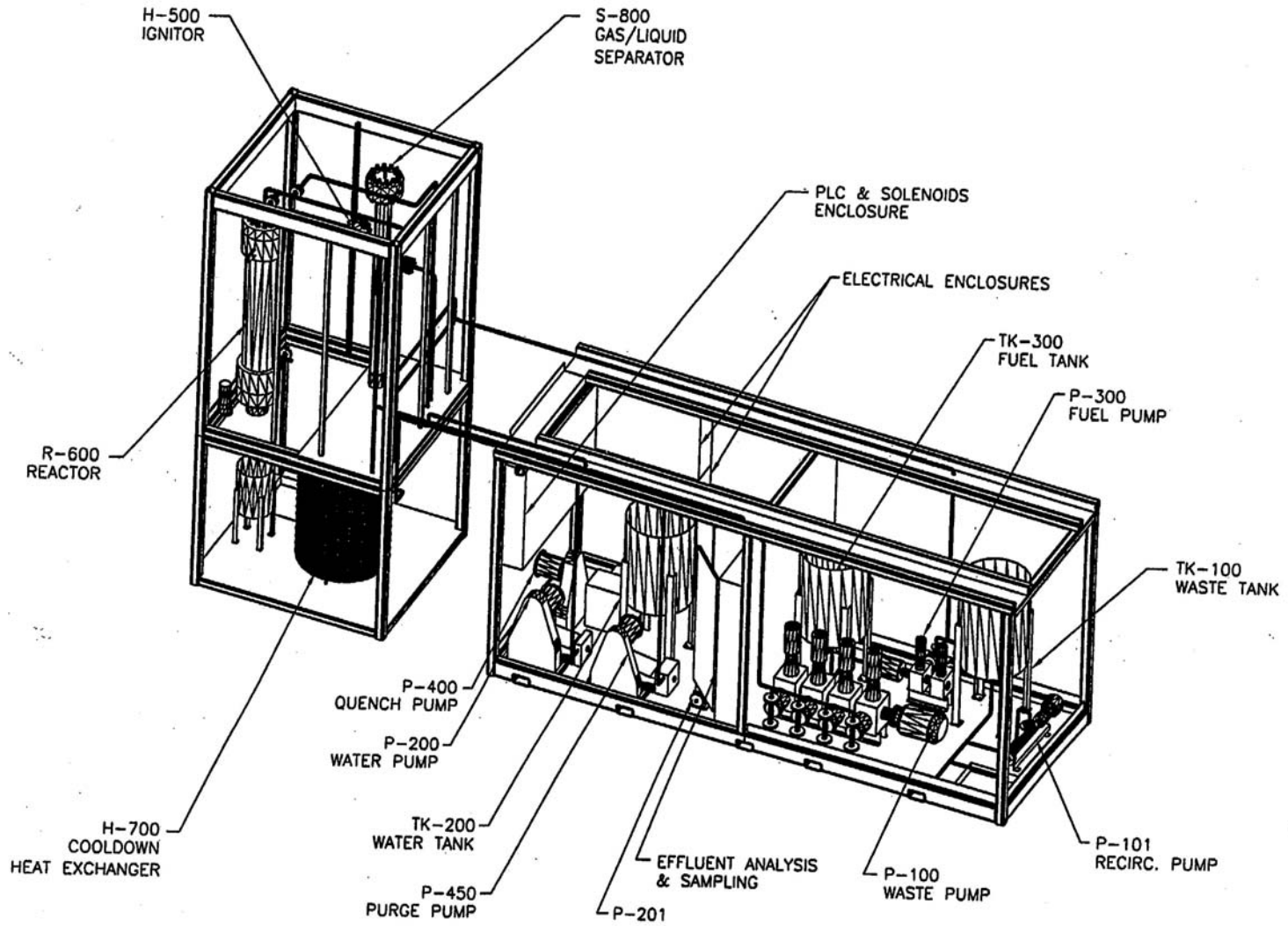
Figure 4-4. SWPO reduced-scale system for 5 tpd of sludge solids coprocessed with waste grease.

Figure 4-5. Encina sludge dewatering building, a potential SWPO reduced-scale demonstration site.

Figure 4-6. Encina sludge conveyor room is available for a SWPO reduced-scale demonstration unit.

The reduced-scale demonstration system will undergo systemization and shakedown testing with progressively more complex feeds. Integrated system testing with sludge solids and waste grease 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 follow-on commercial-scale demonstration at a larger wastewater treatment site.

4.5. BUSINESS PLAN DEVELOPMENT

A business plan has been developed for the commercialization of SWPO distributed hydrogen production by coprocessing of sewage sludge solids and waste grease. Three primary sources of data have been used in developing the plan: (1) costs and other information gathered from wastewater treatment facility operators and equipment suppliers; (2) GA's related experience with SCWO of sewage sludge and hazardous wastes; and (3) economic analysis of the commercial-scale SWPO system presented in Section 5.1. This section describes how the Business Plan was developed. The Business Plan itself is included in Appendix C. The SWPO 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 reduce capital and operating costs sufficiently to support hydrogen production costs well within the competitive market rates for hydrogen of $5 to $14 per GJ targeted by the DOE Hydrogen program.

4.5.1. Methodology and Assumptions

Development of the plan incorporated a series of steps and associated assumptions that progressed from the definition of the optimum size for a commercial SWPO unit through definition of the marketing and financial plans.

Step 1 - Define Optimum Size of Commercial-Scale SWPO System. Sewage sludge-derived solids are produced at all wastewater treatment facilities in the U.S. As part of a market assessment for SCWO, GA sponsored a national survey of municipal wastewater treatment plants carried out by the San Diego State University. The results suggest that there are several hundred plants the size of Encina or larger across the U.S. Thus a plant the size of Encina - 40 tpd total solids or 30 tpd of sewage sludge organics - would be appropriate for a large number of cities or water districts. This size is also a credible factor of eight scale-up of the 5 tpd reduced-scale demonstration system planned for Phase IV.

Step 2 - Define Capital and Operating Costs of Commercial-Scale SWPO System. Based on the 40 tpd size defined in Step 1, capital and operating costs were generated (see Section 5.1). M&EBs for the target plant size were prepared (see Table 3-1) 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 Commercial-Scale SWPO System Costs to Alternate Systems for Hydrogen Generation and Use. Once capital and operating costs were obtained, SWPO hydrogen production costs were compared to the benchmark of $5-$14/GJ, the economic sale price range for hydrogen (Mann et al., 1996). The negative cost of sludge solids disposal

provides a credit that is an important driver in the economic analysis showing that SWPO of sludge solids with waste grease can produce hydrogen at a cost that is competitive with other methods of hydrogen production.

Step 4 - Discuss SWPO Commercial-Scale System with Regional Wastewater Treatment Facilities. The commercial-scale SWPO system was discussed with Encina personnel to obtain their perspective and how they and other wastewater treatment facilities might respond to the proposed method of sludge solids disposal and associated cost savings. Follow-up with other wastewater treatment plants is planned. While Encina has an existing treatment system for sewage sludge, disposal of sludge solids is a significant operating cost, most of which could be avoided with SWPO. This is the initial thrust for deployment of SWPO at wastewater treatment plants. Also of future interest to wastewater plant operators is the potential to discontinue use of some of the treatment equipment associated with sludge treatment. The current treatment systems incorporate large tanks, numerous pumps and valves, and extensive piping for anaerobic digestion of sewage sludge. Avoiding this treatment step, and the subsequent sludge dewatering step was thought to be a long-term advantage for incorporation of SWPO into the plant design. However, initially, SWPO should be introduced as simply an alternative primary and secondary sludge treatment process using a small portion of the treatment plant's capacity. For Encina, with a capacity of 40 tpd of sludge solids, a 5 tpd reduced-scale SWPO demonstration would not upset the normal operations of the site while the demonstration is underway.

The initial 40 tpd commercial-scale SWPO plants should be sited at much larger host sites, such as the San Diego Metropolitan Biosolids Center (MBC) or the Orange County Wastewater Treatment Facility. The MBC has a mixed sludge solids capacity of about 110 tpd, and could accommodate a 40 tpd commercial-scale demonstration without upsetting normal operations. Once commercial-scale SWPO systems have been successfully demonstrated at large wastewater treatment plants, they can be marketed to facilities that have sludge capacities closely matching the SWPO system capacity.

Step 5 - Update Demonstration Program and Related Funding Requirements for Phases II thru IV of the Program. Having determined that SWPO hydrogen production is 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 reduced-scale demonstration planned in Phases II through IV of the DOE program have been updated, and the associated funding requirements have been revised (see Appendix C).

Step 6 - Prepare Financial and Long-Range Marketing Plans. Phases II through IV will be followed by development and demonstration of a commercial-scale SWPO system at a regional wastewater treatment facility. The facility will likely be one of the large municipal wastewater treatment plants in southern California producing 100-200 tpd biosolids. Ideally, a first of a kind SWPO system rated at 40 tpd would not impact the overall operations of the facility. The demonstration will include a year or more of on-site operation to provide first-hand operating experience by facility personnel. Successful demonstration will be followed by design of a standard 40 tpd SWPO system and its commercial sale to wastewater treatment authorities. The financial requirements for the reduced-scale and commercial systems were estimated based on this scenario.

Step 7 - Prepare the Business Plan. Input from Steps 1 through 6 above was integrated into the business plan encompassing SWPO development through reduced-scale demonstration, and preparations for commercial-scale system development and sales.

Please refer to Appendix C for the complete Business Plan.

5. CONCLUSION

A versatile pilot plant for exploring gasification in supercritical water has been established at GA's facilities in San Diego. Phase I testing of the SWPO process progressed to coprocessing of wood and ethanol auxiliary fuel mixtures resulting in gasification efficiencies of about 90%, comparable to those found in prior laboratory-scale work carried out at the University of Hawaii. Unlike the UHM work that was indirectly heated and used catalysts, the GA process is heated mainly by partial oxidation of the feed without a catalyst bed that can cause plugging. As in the UHM work, a significant amount of the hydrogen found in the gas phase products is derived from the water/steam matrix, another benefit of the supercritical regime.

Phase I testing provided the following key findings in the development of SWPO technology:

1. Pumping tests indicate that a slurry feed concentration of about 12 wt% biomass solids is a conservative maximum. Composted municipal solid waste mixed with sewage sludge solids was pumped at about 30 wt% during Phase I, and other observations suggest that 14 wt% sawdust slurries should be pumpable. GA has previously had good success at pumping sewage sludge at solids contents of 10-14 wt%, while literature sources claim that 15 wt% is pumpable. Economic projections utilizing 12 wt% thus represent a conservative minimum. If higher concentrations can be pumped, as appears likely, SWPO economics will be improved.

2. Feed preheat should be limited to 260°C to avoid char formation and plugging. Higher preheat temperatures may be possible with certain feedstocks or with improved heat exchanger designs, but these have not yet been demonstrated by GA.

3. Due to the limitations on feed slurry biomass concentration and feed preheat temperature, a high heating value waste must be coprocessed with the biomass in order to attain the desired gasifier temperature and still have sufficient feedstock for gasification. This is essentially the approach that evolved during Phase I testing, although the high heating value feed was the model compound ethanol as opposed to a waste material. Suitable high-heating value wastes are plastics, rubber, or trap grease.

4. Use a vessel-type gasifier as opposed to a pipe-type gasifier to allow higher gasifier operating temperatures and heat conservation.

5. Use a catalyst-free gasifier to enable long-term operation with dirty feed materials without plugging.

6. Use a high-energy nozzle giving high dispersion of the incoming feed to improve mixing and attain high gasification yields.

7. Use a methane-steam reformer on the clean SWPO product gas.

The Phase I results indicate that a practical means to overcome limitations on biomass slurry feed concentration and preheat temperature is to coprocess an auxiliary high heating value material. SWPO coprocessing of two high-water content wastes, partially dewatered sewage sludge and trap grease, yields a scenario for the production of hydrogen at highly competitive prices. It is estimated that there are hundreds if not thousands of potential sites for this technology across the US and worldwide. Our economic analysis indicates that a broad range of conditions exist for which SWPO can be used to produce hydrogen at competitive prices. Key economic factors include:

1. Biomass credit – Sewage sludge-derived solids are particularly desirable as they generally have a negative value of $200/bdt and higher, are readily available and sustainable as a distributed feedstock, and require minimal size reduction. GA has successfully demonstrated pilot-scale gasification of sewage sludge in prior work for the DOE. Other biomass feedstocks such as waste wood or paper products are also feasible at somewhat less favorable economic projections.

2. High heating value waste cost or credit – Grease trap waste is particularly desirable as a cofeed with sewage sludge solids (SSS) as it generally has a negative value similar to SSS and is as readily available and sustainable as SSS. Avoided costs for disposal of grease trap wastes is about $100 per ton of concentrated grease ($0.08 per wet gallon) or higher. Other high heating value wastes such as waste plastic or rubber and coal are also feasible as cofeeds at somewhat less favorable economic projections.

3. Steam credit – Steam credit is a significant additional offset of operating costs. Much of the steam can be available at 1200 psi if desired.

4. Capital financing rate and term – Particularly favorable financing terms are expected as the targeted customers are municipalities as opposed to commercial entities. Low interest rate 20-year financing has been used for similar municipal projects in San Diego and elsewhere.

5. Ratio of high heating value waste to biomass solids – Higher ratios of high heating value waste lead to a higher proportion of hydrogen production for a given amount of biomass solids processed, further improving the economic projections.

6. Plant size – A plant treating 40 tpd of SSS is economically competitive over a broad range of conditions. In the U.S. there are hundreds of plants of this capacity, serving populations of about 200,000 people.

The economics for 40 tpd SSS plants augmented with grease trap waste are favorable over a significant range of cost parameters such as SSS credit and capital financing. Hydrogen production costs for SWPO plants of this size are projected to be about $3/GJ or less. Economics may be further improved by future developments such as pumping of higher solids content sludges and improved gasifier nozzle designs to reduce char and improve hydrogen yields. The easiest market entry for SWPO is expected to be sales to municipal wastewater treatment plants for use with sewage sludge in conjunction with trap grease, as both of these wastes are ubiquitous and have reasonably well-defined negative value (i.e., the process can

take credit for avoidance of well-defined disposal costs for these streams). Additionally, waste grease is frequently recovered at municipal wastewater treatment plants where it is already contaminated with sewage.

SWPO should also be favorable to other market applications in which low or negative value, high water content biomass is available in conjunction with a low or negative value fuel material. For biomass slurries primary candidates are sewage sludge, manure sludge, and shredded and/or composted organic municipal solid waste (MSW) slurries. For the high heating value stream primary candidates are trap grease, waste plastic or rubber slurries, and coal or coke slurries.

Phase II of the SWPO program will be focused on process improvement scoping tests followed by design, installation and extended duration testing of an advanced SWPO system using the existing GA pilot plant, which has a sludge solids capacity of about 0.1 tpd. Tests of at least 100 hours duration using sludge solids and waste grease as simultaneous feedstocks are a primary objective. Phases III and IV of the SWPO program are directed toward establishing a dedicated 5 tpd reduced-scale plant at a location such as the Encina municipal wastewater treatment plant. Subsequent to this reduced-scale demonstration, the technology will be ready for the commercial-scale, 40 tpd demonstration.

While there are clearly technical challenges that must still be addressed, the proven capability of SWPO to process wet, dirty feedstocks represents an outstanding opportunity to further the dual goals of developing a hydrogen economy and practicing environmentally sound waste disposal. It may well represent one of the few scenarios in which hydrogen can be produced economically from biomass at a relatively small scale. SWPO could thus play a pivotal role in the proliferation of hydrogen generation technology and significantly advance the inevitable transition to a hydrogen economy.

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APPENDIX A

SWPO BACKGROUND INFORMATION

Supercritical water partial oxidation (SWPO) is a combination of two precursor technologies, supercritical water gasification (SCWG) and supercritical water oxidation (SCWO). In SCWG, organic material is exposed to a high pressure steam environment and converted to low molecular weight volatile materials, primarily H_2, CH_4, CO and CO_2. In SCWO, excess oxygen is added to the mix to give essentially complete oxidation of organic material to CO_2 and H_2O and liberation of the heat of combustion. In SWPO, an intermediate amount of oxygen is added to provide some heat release while still producing some H_2, CH_4, CO. All of the supercritical water (SCW) processes take advantage of the properties of supercritical water, a unique state of matter with properties intermediate to those of gases and liquids. This appendix provides background material on SCW, SCWG, and SCWO, followed by some comments on their relation to SWPO.

<u>Properties of Supercritical Water (SCW)</u>

Supercritical water refers to water beyond its thermodynamic critical point of 705°F (374°C) and 3206 psia (22.1 MPa or 218 atm). Reactions in SCW are frequently carried out at conditions of 1200°F and 3400 psi, at which point densities are less than one-tenth that of normal liquid water. At this density water molecules are sufficiently far apart that hydrogen bonding is almost entirely disrupted and the water molecules lose the ordering responsible for many of liquid water's characteristic properties. In particular, the loss of ordering dramatically reduces the bulk polarity of the water as characterized by the dielectric constant.

The loss of bulk polarity by the water phase causes solubility behavior that is closer to that of high-pressure steam than to liquid water. Normally water-soluble salts are no longer readily solvated by water molecules and they precipitate out as solids or dense liquids. Small polar and nonpolar organic compounds, with relatively high volatility, will exist as vapors at typical SCW conditions, and hence will be completely miscible with supercritical water. Gases such as N_2, O_2, and CO_2 show similar complete miscibility. Larger organic compounds and polymers will hydrolyze to smaller molecules at typical SCW conditions, thus resulting in solubilization via chemical reaction. Figure A-1 summarizes the density and typical solubility behavior of compounds in water at 3400 psi as a function of temperature. Figures A-1a and A-1b show the rapid drop in density in the vicinity of the critical temperature, with a concomitant increase in the solubility of nonpolar organics and gases. As shown in Fig. A-1c, high-salt solutions may persist well beyond the critical temperature. This is due to salt stabilization of the dense liquid phase, much as salt raises the boiling temperature of water on a kitchen stove.
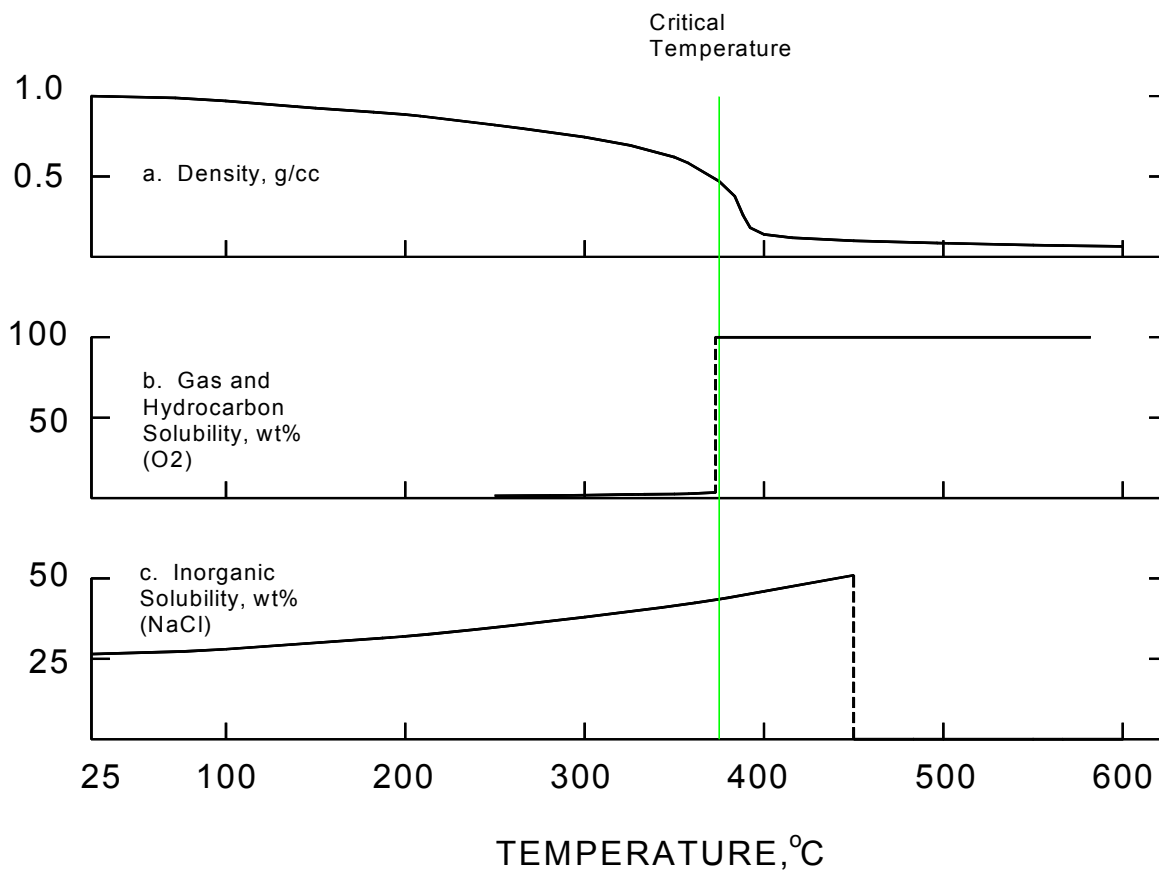
**Fig. A-1. Characteristics of water at 3400 psi as a function of temperature.
a. Density. b. Solubility of nonpolar organics and permanent gases. c. Solubility of
sodium chloride.**

Supercritical Water Gasification (SCWG)

As mentioned above, larger organic compounds and polymers will hydrolyze to smaller
molecules at SCW conditions. This phenomenon has given rise to processes to make liquid
and/or gaseous products in the SCW medium. For the purposes of hydrogen production we are
primarily interested in the gasification reactions.

The earliest tests on gasification in supercritical water were carried out by Modell and coworkers
at the Massachusetts Institute of Technology (MIT) in the late 1970's (Modell et al., 1978).
These tests utilized residence times of at least 30 minutes with temperature and pressure
conditions essentially at water's critical point. Various metallic catalysts were employed. Table
A-1 summarizes some of these laboratory-scale results along with representative data from
more recent testing. Dramatically improved results have been achieved through the use of
higher temperatures and activated carbon catalyst, with reactor residence times as short as 15
seconds. In all cases water is consumed in gas-forming hydrolysis so that the mass of
hydrogen in the gas (including primarily H_2 and CH_4) is higher than the mass of hydrogen in the
organic feed.

Table A-1 indicates that activated carbon catalyst is conducive to high gas yields. It is also clear, however, that this catalyst is not universally required. Furthermore, UHM (1996c) reports that the carbon becomes deactivated over the course of several hours.

It has sometimes been reported that char does not form in the SCWG process. More accurately stated, there appear to be some SCW conditions under which char formation is very low or negligible. There are other SCW conditions, however, where char formation has been observed (GA, 1997; UHM, 1999). Higher organic concentrations appear to be more conducive to char formation. It also seems that the formation of high molecular weight hydrocarbons (tar and char) is a function of feed heat-up time (UHM, 1996c), with longer heat-up times yielding higher amounts of these products.

GA's experience with pilot-scale SCWG of sewage sludge is described in Section 4 of this report.

TABLE A-1. LABORATORY-SCALE SCWG TEST RESULTS

Reference	Feedstock	T, °C	P, psi	Catalyst	Reaction Time, min	%C Gasified	g H gas/ 100 g feed
Modell et al., 1978	Glucose Cellulose	374	3200	Mixed metallic	30	23 18	1.4 0.3
Woerner, 1976	Maple sawdust	374	3200	None	30	88	2.3
Whitlock, 1978	Glucose	380	4750	Mixed metallic	13	36	0.8
Sealock and Elliott, 1991	Cellulose Holocellulose Lignin Wood	400	4000	Ni/Cs$_2$CO$_3$	15	76 70 37 74	6.5 5.1 4.1 7.6
UHM, 1993	Glucose	600	5140	None	0.5	86	11.3
UHM, 1996c	Glucose Bagasse Glycerol	600	5140	Activated carbon Activated carbon None	0.3 1.4 0.75	99 100 100	8.1 3.3 11.8
UHM, 1996a	Cellobiose Water hyacinth	600	5140	Activated carbon	0.3	100 100	5.2 9.4
UHM, 1997b	Corn starch (CS) Sewage sludge + CS Sawdust + CS	650	4170	Activated carbon	0.25	100 94 100	9.1 8.8 9.6

Supercritical Water Oxidation (SCWO)

The SCWO process has been under development since the early 1980's. SCWO laboratory studies quickly established that temperatures considerably higher than the critical temperature of water (374°C), in the range of 600 °C, were desirable to achieve rapid and complete oxidation. In contrast, the pressure functionality was more ambiguous, with good oxidation result being reported at pressures both considerably below and above the critical pressure of 3206 psi (Hong, 1992; Buelow et al, 1990). (For simplicity, the process is still referred to as SCWO, even though the operating pressure may be somewhat subcritical.) The molecular dispersion of the organic and oxidant reactants within a single phase, in conjunction with the high diffusivity, low viscosity, and relatively dense SCW reaction medium, is conducive to rapid oxidation reactions. Furthermore, the temperature is sufficiently high that reaction completion is usually attained within seconds to tens of seconds.

SCWO has proven to be a robust method for the complete oxidation and mineralization of a wide spectrum of materials. Applications of SCWO technology have thus far been primarily targeted at waste destruction applications, where the high destruction efficiencies attainable in compact equipment are very desirable. The process has the capability of operating on a wide range of feed materials, including wet or dirty fuels such as sewage sludge, MSW, or high-sulfur coal. The effectiveness of SCWO has been demonstrated at the laboratory and pilot scale on hundreds of feedstocks. Feedstocks of interest to the current program that have been treated by SCWO include sewage sludge (General Atomics, 1997), black and gray water (GA, 2000), coal slurry (Modar, Inc. unpublished results), pig manure (Rulkens et al., 1989), various biomass slurries including pulp mill sludge (Modell, 1990), pulverized wood with ground plastic, rubber, and charcoal (General Atomics, 1999), fermentation waste (Johnston, et al., 1988) and ground cereal (Hong, et al., 1996). Complete oxidation of virtually any organic material, including highly refractory hazardous wastes such as hexachlorobenzene, has been demonstrated. Regardless of the particular feedstock, the heat of combustion is captured directly within the high-pressure aqueous stream without the need for intervening heat transfer surfaces.

The low temperature of SCWO in comparison to normal combustion has the advantage of reducing NO_x and SO_x formation. Typical effluent levels for these gases, even with nitrogen-containing feeds and air oxidant, is less than 1 ppm.

Supercritical Water Partial Oxidation (SWPO)

Like SCWO, SWPO has an inherent advantage over external heating in that the heat of reaction is generated in situ, without the need for any intervening heat transfer surfaces. Thus, the problems of scaling heat transfer surfaces and limited metal strength at high temperatures are largely avoided. Use of pure oxygen or highly enriched air as the process oxidant minimizes the inert gas content of the steam.

As with SCWG and SCWO, rapid reaction times and a relatively dense medium make for compact, heat-efficient equipment in the SWPO process. Compact equipment and heat conservation are the primary factors behind the use of elevated pressures in coal gasification.

Like SCWO, the SWPO process has the capability of operating on a wide range of feed materials, including wet or dirty fuels such as sewage sludge, MSW, or high-sulfur coal.

APPENDIX B

SWPO TEST PLAN (APRIL 2001)

This is the original test plan prepared early in Phase I. During the course of Phase I testing, significant departures were taken from this plan, but the plan was not subsequently updated. However, the plan does provide a basis and context for the work carried out in Phase I. Generally, the departures made from the test plan were due to limitations in the test equipment or unanticipated complications that could not be overcome within the budget and schedule constraints of Phase I. These issues are discussed in the body of the report.

1.0   OBJECTIVES

The objectives of the Supercritical Water Partial Oxidation (SWPO) test program will be to demonstrate the potential for economic hydrogen production with minimal or manageable char formation using negative value feedstock. Shakedown tests will be conducted using a model compound that will allow comparison of the test results to results from supercritical water gasification tests. Coal and raw compost will also be tested, as these fuels represent potential fuels for large-scale gasification plants.

The objectives of the test program are to:

- Demonstrate the feasibility of the SWPO process
- Determine the effect of the following process parameters on the Hydrogen yield:
  – Solids concentration
  – Reactor residence time
  – Reactor configuration
- Demonstrate that raw compost can be gasified economically by SWPO
- Determine the operating conditions for a full-scale SWPO demonstration plant
- Develop a material and energy balance and develop a process flow diagram for a full scale SWPO demonstration plant

2.0   DESCRIPTION OF EQUIPMENT

The General Atomics SWPO pilot plant has been designed to be a very flexible test apparatus for studying oxidation, partial oxidation and gasification in supercritical water. The pilot plant is equipped with a boiler capable of producing 500 lb/hr (3,780 g/min) of steam or supercritical water. There is also a heat exchanger that can be used to transfer heat from the reactor effluent to the incoming feed stocks. The pilot facility is equipped with two reactors: a downflow reactor which is 2.8 inches (71.12 mm) inside diameter and 40 inches (101.6 cm) long; and a tubular reactor which consists of 5 heated sections, 0.861 inches (21.87 mm) inside diameter and 1,065 inches (2,682 cm) total in length. All of the reactors have a maximum working pressure of 4,500 psig (31.1 MPa) and a maximum working temperature of 1250 °F (676 °C). The maximum flow rate through the downflow reactor is about 70 lb/hr and the maximum flow rate through the tubular reactor is about 175 lb/hr.

Solids are mixed with water up to a feed concentration of 40 % by weight. This mixture is then pumped up to reactor pressure and mixed with hot water, which is at reactor pressure and 1,112 °F (600 °C), in a mixing tee. Mixing the hot water with feed in a 2:1 water to feed ratio, will

result in a reactor feed that has a solids concentration of approximately 13% at a temperature over 780 °F (415 °C), which is well above the temperature where char forms.

Oxygen can either be premixed with the hot water prior to entering the mixing tee, or it can be added downstream of the mixing tee. By premixing the O_2 with the water up stream of the mixing tee, the reaction products can be brought up to test temperatures almost instantaneously.

After exiting either the downflow reactor or the tubular reactor, the reactor effluent is cooled to room temperature by water in a heat exchanger. The downflow reactor is also equipped with several quench points, at several different elevations in the reactor, where the effluent can be rapidly cooled by being mixed with an excess of water. These quench points allow the chemical reactions to be stopped quickly in order to study the reaction kinetics. Once cooled, the effluent passes to a flash vessel where gases are separated from the liquid, while the effluent is still under pressure. Control valves, connected to the gas and liquid exit streams, control the pressure in the apparatus. Part of the gas stream is then fed to the continuous gas analyzer system where it is analyzed for CO_2, CO, CH_4, O_2, and H_2. Samples of the liquid effluent can also be taken for further analysis.

One drawback to this arrangement is that CO_2 dissolves easily in water at the pressures encountered in the flash tank (Divilio 1998). This will help to enrich the gas stream, by removing part of the CO_2. However, it will make analyzing the test data more onerous because the CO_2 in the liquid effluent will either have to be measured or it will have to be estimated using the Henry constant of CO_2 at the conditions in the flash tank. This will be particularly troubling when the reactor quench mechanism is used, because the additional water will dissolve more of the CO_2. While this is not an undesirable result in a commercial operation, it will make closing the carbon balance more difficult. To improve the carbon balance, the liquid stream will be sent to a secondary flash vessel after the pressure as been reduced and the flow rate of gases leaving the top of this vessel will be measured and analyzed along with the liquid effluent.

This test program will concentrate primarily on the downflow reactor. If time permits, a test will also be conducted in the tubular reactor to see if the reactor configuration has an impact on the final reaction products. The various quench levels in the downflow reactor will be used to stop the reaction at various times to allow preliminary analysis of the overall reaction kinetics. Because the quench water will cool the reaction products, the feed heat exchanger can not be used to transfer heat from the reactor effluent to the incoming water for these tests. Instead, heated water from the boiler at 1,112 °F (600 °C) will be mixed with the incoming feed paste to simulate the heat exchange step.

3.0 FUELS

Three fuels will be tested in the Supercritical Water Partial Oxidation Pilot Plant. Cornstarch will be the first fuel tested. The University of Hawaii (UHM, 1997a) has tested cornstarch extensively in their supercritical water pyrolysis equipment. As such this fuel will serve as a baseline for comparisons to the supercritical water gasification process.

In addition to cornstarch, which is a fairly easy material to mix and feed, two solid fuels will also be tested. The first will be coal/water slurry, which contains at least 40% by weight dry coal. The coal water slurry will either be purchased as pre-mixed slurry or will be manufactured at the pilot plant. The type of coal tested will depend on the availability of coal water slurry. The second solid fuel is a mixture of composted sewage sludge and MSW called Raw Compost. General Atomics has found that they can produce a slurry that contains 40% by weight dry solids using this material, and it is easily pumped up to supercritical pressure. This material is also readily available and could be a good source of fuel for a larger hydrogen plant.

Because the sludge exists in only limited quantities in any single location, a test will also be conducted using mixtures of coal and raw compost if time permits. The goal of this mixed fuel test will be to test a mixture of 50% raw compost and 50% coal at a feed concentration of 40% by weight of dry solids. If such a mixture can not be easily pumped then a mixture of 75% sludge and 25% coal in a feed concentration of at least 40% by weight of dry solids will be tested.

4.0 TEST MATRIX

The current program has only a limited amount of time allocated for testing the pilot plant. A large majority of that time will be spent commissioning the apparatus and ensuring that the data from the test program is of the highest quality. It is estimated that this program will have about 5 days available for data acquisition after the equipment is commissioned. During a test day, it is estimated that 3, or at most 4 test periods can be achieved, assuming about 2 hours to steady state between test conditions. Accordingly, the test matrix has been set-up on the basis of three test periods in a single test day. A fourth test condition will also be specified with the test number designation #-TP indicating that this test condition will be tested if time permits. Furthermore, in case the shakedown and commissioning of the pilot plant takes less time than anticipated, two test additional test series will also be described that will be conducted if time permits. These are designated Series 6-TP and Series 7-TP.

Test Series 1 and 2 will be conducted using the model compound cornstarch in the downflow reactor and using the quench system to study the reaction kinetics. The conditions for these two test series will be nearly identical; the only difference being that, in Series 2, the cornstarch paste feed will be heated to 300 °C prior to entering the mixing nozzle to minimize the use of oxygen and to improve the yield of hydrogen. Test Series 3 will be conducted using coal water slurry as the feed to the downflow reactor. Test Series 4 and 5 will be conducted using the raw compost in the downflow reactor with the raw compost being heated to 300 °C prior to the mixing tee in Series 5. If time permits, Test Series 6-TP will be conducted using a mixture of 50% raw compost and 50% coal in a feed concentration of 40% by weight of dry solids. Finally, Test Series 7-TP will be conducted using cornstarch and the tubular reactor, at the same test conditions as Series 1, if time permits.

All of the tests will be conducted utilizing the same basic operating procedures. The reactor will be brought up 1,112 °F (600 °C) and test pressure using the hot water from the boiler flowing at the maximum throughput for the reactor. Once the temperatures have stabilized, the water flow will be reduced to the flow rate for the first test of the series. Next the O_2 feed will be set at a minimum flow rate of about 1 lb/hr (7.6 g/min). Finally the fuel paste feed will be initiated at the

flow rate for the first test. Oxygen feed will then be increased or decreased until the test temperature of 650 °C is established. All conditions will be kept at steady state throughout the data collection period.

4.1   Cornstarch Tests

Three test series are planned using cornstarch as the feed. Series 1 will be conducted using the downflow reactor and various quench levels to study the effect of reaction time on the hydrogen yield. Series 2 will be identical to Series 1 except that the cornstarch paste will be heated to 300 °C prior to being fed to the mixing tee. The paste will be heated in a section of the tubular reactor, which is electrically heated. The additional heat should result in a decrease in the amount of oxygen needed to bring the reactants up to 650 °C resulting in improved hydrogen yield. Test Series 6-TP will be conducted using unheated cornstarch feed to the tubular reactor.

4.1.1   Series 1

Series 1 will consist of 3 (possibly 4) tests using the downflow reactor. All tests will be conducted at a reactor pressure of 4075 psig (28 MPa) with oxygen being fed upstream of the mixing tee. The pressure and temperature for these tests were chosen to allow comparison to the cornstarch data from the University of Hawaii. The feedstock for this test will be a 40% by weight mixture of cornstarch and water. Table B-1 lists the conditions for the Series 1 tests.

TABLE B-1. TEST MATRIX FOR SERIES 1

Test No.	Paste Feed, g/min	Hot Water Feed, g/min	Quench Water Level, in.	Paste Temp, C	Reactor Temp, °C	Cornstarch Conc. wt. %	Test Duration Hours
1A	105	300	39	25	650	10.4	1.0
1B	105	300	23	25	650	10.4	1.0
1C	105	300	3	25	650	10.4	1.0
1D-TP	150	300	39	25	650	13.3	1.0

Quench water level in Table 1 is indicated as measured from the entrance of the reactor. In this series, changes to the oxygen feed rate will be used to control reactor temperature. The tests will study the effect of residence time in the reactor. Oxygen requirements for these tests range from 2 to 2.8 lb/hr (15 to 21.2 g/min). Tests 1A, 1B, and 1C represent the feed conditions for the University of Hawaii's tests on cornstarch.

4.1.2   Series 2

Series 2 will test preheating the cornstarch feed paste up to 300 °C prior to feeding to the mixing tee. By heating the paste feed, the oxygen requirements should be decreased by about 30%, which should increase the hydrogen yield. All tests will be conducted at a reactor pressure of 4075 psig (28 MPa) with oxygen being fed upstream of the mixing tee. The feedstock for this test will be a 40% by weight mixture of cornstarch and water. Table B-2 lists the conditions for the Series 2 tests.

TABLE B-2. TEST MATRIX FOR SERIES 2

Test No.	Paste Feed, g/min	Hot Water Feed, g/min	Quench Water Level, in.	Paste Temp, C	Reactor Temp, °C	Cornstarch Conc. wt. %	Test Duration Hours
2A	105	300	39	300	650	10.4	1.0
2B	105	300	23	300	650	10.4	1.0
2C	105	300	3	300	650	10.4	1.0
2D-TP	150	300	39	300	650	13.3	1.0

The test conditions for this series of tests are the same as the ones used for Series 1. At the end of this test series, the mixing nozzle and the paste feed heater will be carefully examined for evidence of carbon formation. In addition, the reactor effluent will also be examined carefully for char.

4.1.3 Series 7-TP

This test series will be run after Series 1 through 5 and 6-TP are completed, if time permits. The purpose of this test series is to observe the effect that the reactor configuration has on the hydrogen yields. For this series, the tubular reactor will be utilized. The reaction time in the tubular reactor is set by the flow rate of fluid through the reactor. The time in the downflow reactor for Tests 1A and 2A is estimated to be about 42 seconds. In order to achieve this reaction time in the tubular reactor the flow rate of material will have to be about 2.56 times greater than the flows in the downflow reactor. Test 7A-TP will match the residence time in the downflow reactor of 42 seconds. The remaining tests will look at the effect of longer residence times by decreasing the flow rate through the reactor.

The oxygen feed will be located upstream of the mixing tee as in Series 1. The concentration of cornstarch in the feedstock will be 40% by weight, and the reactor pressure will be 4075 psig (28 MPa). Table B-3 lists the test conditions for Series 7-TP.

TABLE B-3. TEST MATRIX FOR SERIES 7-TP

Test No.	Paste Feed, g/min	Hot Water Feed, g/min	Paste Temp, °C	Reactor Temp, °C	Cornstarch Concentration wt. %	Test Duration Hours
7A-TP	270	770	25	650	10.4	1.0
7B-TP	270	385	25	650	16.5	1.0
7C-TP	135	385	25	650	10.4	1.0
7D-TP	105	300	25	650	10.4	1.0

Test conditions for test 7A-TP are approximately the same as for Test 1A. The other tests look at the effect of feed concentration and residence time.

4.2 Solid Fuel Tests

Test Series 1 and 2 will provide valuable information regarding the performance of heavily oxygenated compounds under SWPO conditions. However, there is another class of organic compounds that contain considerably less oxygen than cornstarch. These compounds include coal and raw compost. Because these compounds contain less oxygen than the cornstarch, they will have a higher requirement for, oxygen per pound of dry fuel, to bring the reactants up to the test temperature.

4.2.1   Series 3 Coal

Because of the availability of coal, this fuel would be an ideal gasification fuel for very large-scale plants. In this test series, a coal/water slurry containing 40% by weight coal in water will be used for the feed paste. Oxygen feed will be upstream of the mixing tee. The downflow reactor will be used for these tests at a pressure of 4075 psig (28 MPa).

In this series, two, or possibly three if time permits, concentrations of coal in the stream leaving the mixing tee will be tested, ranging from 8% to as high as 13.3% by weight. Feed rates of paste and water were chosen so that the oxygen demand to achieve the test temperature does not exceed the feed limits of 5 lb/hr. The feed stream of the coal water slurry will not be heated in these tests. Furthermore, in all of these tests, the quench level in the down flow reactor will be 39 inches to provide the longest possible residence time for the solid fuel to be consumed. Table B-4 lists the test conditions for Series 3.

TABLE B-4. TEST MATRIX FOR SERIES 3

Test No.	Paste Feed, g/min	Hot Water Feed, g/min	Paste Temp, °C	Reactor Temp, °C	Coal Concentration wt. %	Test Duration Hours
3A	75	300	25	650	8.0	1.0
3B	100	300	25	650	10.0	1.0
3C	170	510	25	650	10.0	1.0
3D-TP	170	350	25	650	13.1	1.0

In all of these tests, the mixture of coal and water leaving the mixing tee will contain coal in excess of the amount that could be burned by the oxygen being fed. Therefore, there will be some solid char that will be free to react with the supercritical water. If this reaction occurs forming CO, which will further react with water to form hydrogen and CO_2, then there exists the potential for hydrogen yields in excess of 100% of the hydrogen being fed to the reactor in the coal. The reactor effluent from these tests will be studied carefully to determine the fate of this free char. Oxygen demand for these tests is expected to range from 2.1 to 4.4 lb/hr (15.9 to 33.3 g/min)

4.2.2 Series 4 Raw Compost

General Atomics has found that they can produce raw compost slurry, which contains over 40% by weight solids, and can still be fed through a pump. Because this material represents a promising feedstock for a larger hydrogen plant, it has been chosen for testing in this program. In this series raw compost will be tested in the downflow reactor at a pressure of 4075 psig (28 MPa).

The raw compost is very high in ash (about 25% of the dry solids is ash). Therefore, in spite of the fact that the concentration of raw compost after the mixing tee will be as high as 13.3% by weight, the concentration of organics will be somewhat lower than that. Also, because the sludge is higher in oxygen than coal, the oxygen demand for this fuel will be slightly lower than the oxygen demand for the coal tests. Table B-5 lists the test conditions for Series 4.

TABLE B-5. TEST MATRIX FOR SERIES 4

Test No.	Paste Feed, g/min	Hot Water Feed, g/min	Paste Temp, °C	Reactor Temp, °C	Solid Concentration wt. %	Test Duration Hours
4A	75	300	25	650	8.0	1.0
4B	100	300	25	650	10.0	1.0
4C	170	510	25	650	10.0	1.0
4D-TP	170	350	25	650	13.1	1.0

4.2.3 Series 5 Raw Compost

In this test series, raw compost will again be tested. This time the feed paste will be heated to 300 °C using hot water from the boiler. All other conditions for this test series will be the same as for series 4. Table B-6 lists the test conditions for Series 5.

TABLE B-6. TEST MATRIX FOR SERIES 5

Test No.	Paste Feed, g/min	Hot Water Feed, g/min	Paste Temp, °C	Reactor Temp, °C	Solids Concentration wt. %	Test Duration Hours
5A	75	300	300	650	8.0	1.0
5B	100	300	300	650	10.0	1.0
5C	170	510	300	650	10.0	1.0
5D-TP	170	350	300	650	13.1	1.0

4.2.3   Series 6-TP Sludge and Coal

This test series will be conducted if time permits. In Series 6 a mixture of the raw compost will be mixed with coal. The goal of this series will be to utilize a mixture that is 50% raw compost and 50% coal by weight in slurry that is 40% by weight dry solids. However, if 40% slurry proves to be impossible to pump, slurry consisting of 75% raw compost and MSW plus 25% coal will be tested.

In this series the tests will be conducted in the downflow reactor with the 39 inch quench level. Table B-7 shows the test conditions for Series 6 assuming the 50-50 mixture can be pumped up to test pressure. If the 75-25 mixture is used, the flow rates will be the same, assuming the concentration of the sludge is 40% by weight dry solids.

TABLE B-7. TEST MATRIX FOR SERIES 6-TP

Test No.	Paste Feed, g/min	Hot Water Feed, g/min	Paste Temp, °C	Reactor Temp, °C	Solids Concentration wt. %	Test Duration Hours
6A-TP	75	300	TBD	650	8.0	1.0
6B-TP	100	300	TBD	650	10.0	1.0
6C-TP	170	510	TBD	650	10.0	1.0
6D-TP	170	350	TBD	650	13.1	1.0

The paste feed temperature will be determined based on the results of Series 4 and 5. This test series will only be conducted if Series 1 through 5 are completed with sufficient test time remaining in the program.

4.3   Test Matrix Summary

Overall a total of 15 separate tests will be conducted during this test program, with an additional 13 tests if time permits. Of these, between 6 and 12 tests will be conducted using cornstarch, 3 or 4 will test coal/water slurry, and 6 or 8 will test raw compost. An additional 3 or 4 will test a mixture of the raw compost and coal if time permits. All of the solid fuel tests were designed to provide data at three solid concentrations and three reactor flow rates.

It should be pointed out that, because of the exploratory nature of this test program, it is possible that the test conditions listed in this plan could change, depending on results of earlier tests. If this proves to be the case, a revised test plan will be issued prior to the resumption of testing. Furthermore, if time permits, a more detailed parametric test program could be started to examine other test conditions, such as reactor pressure, reactor temperature, and feed concentrations.

5.0 DATA REDUCTION

Carbon, hydrogen and total mass balances will be performed for all of the test periods. During the solid fuel tests, ash balances will also be performed. Furthermore, during one of the Series 3 tests, the coal/water slurry series, samples of all incoming and exiting streams will be analyzed for sulfur in order to perform a sulfur balance. A sulfur balance will be critical to any process that gasifies coal in order to determine the fate of the fuel bound sulfur.

Hydrogen yield will also be calculated as a percentage of the mass of hydrogen gas that is produced divided by the weight of hydrogen in the dry fuel entering the process. Note it is anticipated that the hydrogen yield from the SWPO process will be lower than the hydrogen yield from a supercritical gasification process operating under the same conditions. This is because some of the fuel is burned in the reactor, rather than externally to the reactor, as would be the case for a gasification process.

A total gaseous hydrogen yield will also be calculated. This yield includes the hydrogen in the methane gas produced as well as the free hydrogen. This value will be an important number because it will indicate whether any water is being consumed by the gasification reactions. A total gaseous hydrogen yield greater than 100% will show that water is being split by the reactions.

Energy balances will not be possible for these tests. This is because the reactors are heated with electric resistance heaters to supplement their insulation and the energy input to the heaters is not measured. However, the ratio of the chemical energy in the gas stream divided by the chemical energy in the feed will be calculated. This ratio will provide some measure of the thermal conversion of this process.

6.0 CHEMICAL ANALYSES

The SWPO pilot plant is equipped with on-line gas analyzers to measure the composition of the gaseous products from the reactor. These analyzers include CO_2, CO, CH_4, O_2, and H_2. These analyzes will provide a continuous record of the composition of the gas stream during the tests.

The mass balances will require analyzing the feed stock and the liquid effluent from the reactor in addition to the gas measurements. The feed paste should be analyzed for the following compounds:

Water
Carbon
Hydrogen
Nitrogen
Sulfur
Ash
Oxygen (by difference)
Higher Heating Value (HHV), Btu/lb

These analyses are typical analyses performed during an Ultimate analysis of coal.

Since one batch of fuel paste will be mixed for each test series, only one analysis is needed for the solid fuel in the paste. The paste will be stored in a continuously stirred tank to ensure uniformity of the feed concentration. A 100-gram sample of the feed paste should be taken during each test as close to the feeder as possible and marked with the time the sample was taken. These samples should be weighed and then dried separately in an oven at a temperature of 110 °C until there is no further weight loss. The initial and final weights should be recorded and used to calculate the water content of the feed paste for each test. After the samples have been dried, they should be blended to form one composite sample of the solids that is representative for the entire test series. This sample can then be sent out to an independent laboratory for an ultimate analysis.

Since cornstarch is quite uniform in composition, it only needs to be analyzed once before it is mixed with the water to form the feed paste. If the cornstarch used for all of the test series is from the same shipment, it will not need to be analyzed separately for each test series. However, if a different shipment is used, then one sample from each shipment of cornstarch will be required. Moisture determinations, described above, should be performed for every cornstarch test period.

The liquid effluent stream should be analyzed for CO_2 and total organic carbon (TOC). During the solid fuel tests, the liquid effluent stream should also be analyzed for ash and carbon in the ash. Carbon in the ash will be an important indicator of the amount of char remaining after the gasification process. While thermodynamics predicts that all of the char will react with water, the rate of this reaction will have a bearing on the final char concentration in the ash stream. The two reactor flow rates used for the solids fuel tests at the 10% feed concentration will provide insight into this reaction rate.

During Test 3C, a sulfur balance will also be performed. This will require an analysis for sulfur in the gaseous stream and in the liquid effluent. Grab samples of these two streams will be taken during this test for analysis. The gaseous stream should be analyzed for H_2S. The liquid effluent should be analyzed for H_2S and H_2SO_4 and the ash in the liquid effluent should be analyzed for sulfur.

7.0   DATA ACQUISITION

The SWPO pilot plant is equipped with a data acquisition system which continuously records temperatures and pressures throughout the apparatus. The data acquisition system also continuously records the gas analyses from the gas analyzer system. The flow rates of hot water, paste feed, oxygen, cooling water, gas produced from the high pressure flash tank, gas produced from the low pressure flash tank, and liquid effluent will also be recorded either by the data acquisition system or by hand during the tests. The gas and liquid effluent flow rates will be measured upstream of any point where samples are removed for analysis. Any measurement that is hand recorded will be taken at least three times during the tests period, once at the beginning, once in the middle and once just before the end of the data acquisition period. All data taken during a test period will be averaged over the duration of the test to give an average measurement for the test.

The downflow reactor and the tubular reactor are equipped with several thermocouples located at various locations in the reactor. The average of al these thermocouples will be considered the test temperature when reporting the test results. Temperature profiles will be plotted to determine if any temperature variations exist throughout the reactor.

8.0   REFERENCES

1. Divilio, R. J., "Gas Clean-up Model for the University of Hawaii's Supercritical Water Reactor, Activity 3 Report " NREL Report, Subcontract Number AXE-8-17103-01, July 24 1998.

2. Antal, J. A. Jr. and X. Xu, "Hydrogen Production from High Moisture Content Biomass in Supercritical Water", Proceedings of the 1998 US DOE Hydrogen Program Review Meeting, Alexandria, VA, April 28-30, 1998.

APPENDIX C

BUSINESS PLAN

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. Due to its ability to process negative and low value feedstocks, supercritical water partial oxidation (SWPO) has been found to be competitive with other means of producing hydrogen from biomass, and in the competitive range with steam reformed methane gas. SWPO of biomass has the potential to produce hydrogen from feeds with high moisture or hazardous waste content not suitable for gasification by other means, e.g., sewage sludge solids, waste grease, and municipal solid waste. SWPO is a compact high-pressure process that produces hydrogen at elevated pressure, ideal for storage. SWPO is also an environmentally clean process producing clean water and gaseous effluents, plus ash for disposal. The SWPO processing of low-value feeds, particularly sewage sludge solids coprocessed with grease trap waste, can result in hydrogen production costs that are significantly lower than those associated with biomass feeds derived from a dedicated feedstock supply such as energy crops. Thus sewage sludge solids can be viewed as one of the primary biomass feeds for cost-effective hydrogen production and power generation using SWPO. While alternative sludge solids disposal methods exist or are being developed, virtually all involve cost penalties to wastewater treatment facility operators. The identification of low or negative value feedstocks with high heating value such as grease trap waste to coprocess with the sludge solids is another key to the economic production of hydrogen using SWPO.

There exist several factors that may limit the near-term applicability of SWPO 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 SWPO-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 end users. Thus near-term economic justification for SWPO system sales would be driven mainly by avoided sludge solids disposal costs or similar local circumstances instead of revenue from hydrogen generation. This might lead to the initial use of SCWO, the oxidation precursor technology to SWPO, for disposal of sludge solids at reduced disposal costs. Market entry with SCWO would minimize impact on the facility. SCWO is a mature technology that is beginning to enter the sewage sludge market in the U.S. and abroad. Eventually, as SWPO matures, the SCWO plants could be retrofitted to SWPO plants for hydrogen production at about the same time a market is emerging for distributed hydrogen consumption for fixed and mobile fuel cell applications.

A second factor is the relative immaturity of the SWPO technology vis-à-vis that which is normally accepted as viable and market-ready for large-scale, commercial installations. While both laboratory- and pilot-scale SWPO tests have shown favorable generation of hydrogen from biomass, they are limited in duration. However, they form a strong basis for additional testing to demonstrate long-term performance of the SWPO process. Phase II of the ongoing program with the DOE will include extended duration testing of sludge solids and waste grease in order

Market Analysis

Market Definition

The near-term market for SWPO technology is the processing of biomass streams for which substantial disposal costs are currently involved. Leading candidate wastes include sewage sludge, municipal solid waste, animal manures, pulp and paper mill sludges; agricultural/food processing wastes such as bagasse, wheat straw, potato peelings, corn stover, and fruit processing residues. These wastes are characterized as having high moisture content and some have toxic or corrosive chemicals that are difficult to handle by more traditional gasification methods. Potential low or negative cost, high heating value feedstocks include grease trap waste, waste plastic and rubber, waste oil, coke, and low-grade coal.

A municipal treatment plant serving a city of 1 million residents will generate about 100 tpd of digested sewage sludge solids (Bastian, 1997). Undigested sewage sludge solids are produced at approximately double this rate. A city of 200,000 residents can thus support a SWPO plant of the size proposed for initial commercial installations (about 40 tpd) when operating on undigested sewage sludge solids. To define the prevalence of this size community, Table C-1 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 40 tpd or larger SWPO 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 C-1. 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.

Earlier this year a wastewater treatment plant survey was carried out by GA in conjunction with San Diego State University (SDSU). Utilizing the world-wide web, electronic surveys were delivered to about 1000 wastewater treatment directors. About 120 responses were received. A full report on the survey has been included as Appendix D.

to demonstrate technology maturity and support the development in Phases III and IV of a reduced-scale (5 tpd) demonstration plant at a municipal wastewater facility such as Encina.

The following sections of the business plan present the framework for development of SWPO 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., fossil fuel reforming).

2.   Continuing development and scale-up of the SWPO process in Phases II through IV and verification of performance and cost projections.

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 SWPO development and commercialization. For the sake of clarity, the name "SWPO Systems" will represent the business entity in the remainder of the business plan.

Vision and Mission

Our vision is that SWPO Systems will become a dominant source for environmentally friendly, sustainable production of hydrogen in the 21st century. To realize this vision, our mission is to become the provider of reliable, cost-effective SWPO systems and services for the production of hydrogen and power from biomass. Our near-term focus for the business will be to provide systems and services to the wastewater treatment industry for the disposal of sludge solids together with waste grease and concomitant production of hydrogen. As we develop the technology and market for SWPO, we will expand our target market to other large, reliable sources of low or negative-value biomass such as sorted MSW, animal wastes, forest product wastes, as well as low grade fossil fuels such as high-sulfur coal or petroleum coke.

Goals and Objectives

The primary goals and objectives for development of SWPO as a successful business for hydrogen production are described below. Fig. C-1 presents a summary timetable of pre-commercial (Phase II), near-commercial (Phases III and IV) and commercial activities.

1.   **Complete pilot-scale development and demonstrate reliable, cost-effective operation of SWPO reduced-scale system.** Under Phases II through IV of the GA/DOE program preceding commercial activities, additional pilot-scale testing will be performed during Phase II with sludge solids, grease and other targeted feedstocks, followed by the development of a one-eighth commercial scale (5 tpd) system during Phases III and IV to demonstrate the SWPO process at reduced-scale. The results of this 6-year development program will validate the process

performance, reliability, and economic projections for the SWPO process. The 5 tpd reduced-scale 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 SWPO for sludge solids treatment and hydrogen production. Design of a commercial-size SWPO system will likely begin during the latter part of this work, incorporating lessons learned from on-site testing and operations. Simultaneously, active marketing of SWPO systems will begin with the wastewater industry, with the intent of acquiring the initial customer for the system.

2. **Sell the initial SWPO commercial-scale system.** Based on successful completion of testing of the reduced-scale SWPO system at a wastewater treatment facility, the first commercial SWPO system will be sold to a large wastewater treatment facility, possibly with a lease-back provision to an independent operating company. The initial commercial plant size, 40 tpd, is compatible with the processing rate of a large number of wastewater treatment facilities and represents a credible eight-fold increase in throughput over the reduced-scale system. Following successful operation of this unit, additional sales of this size unit are anticipated.

Product Strategy

With the successful completion of Phase I, the remaining pre-commercial research and development is embodied in Phase II of the GA/DOE SWPO technical plan. The remaining tasks are defined that build on work to date in Phase I of the GA/DOE program. Scoping tests will be performed in the GA pilot plant to resolve remaining technical issues. Then the pilot plant will be upgraded with advanced SWPO system components and tested with target feedstocks for extended durations.

Phase III, System Integration and Design, is focused on design and long-lead procurement for a new reduced-scale system. Phase IV, reduced-scale demonstration of a 5 tpd system, will complete the fabrication and systemization of the near-commercial system and then verify performance, reliability, and process economics at a wastewater treatment facility.

ID	Task Name	2003	2004	2005	2006	2007	2008	2009	2010	2011
1	Technology Development (GA/DOE Phase II)									
2	System Integration and Design (GA/DOE Phase III)									
3	Reduced-Scale Demonstration of 5-tpd System (GA/DOE Phase IV)									
4	Design and Construction of 40 tpd Commercial System									
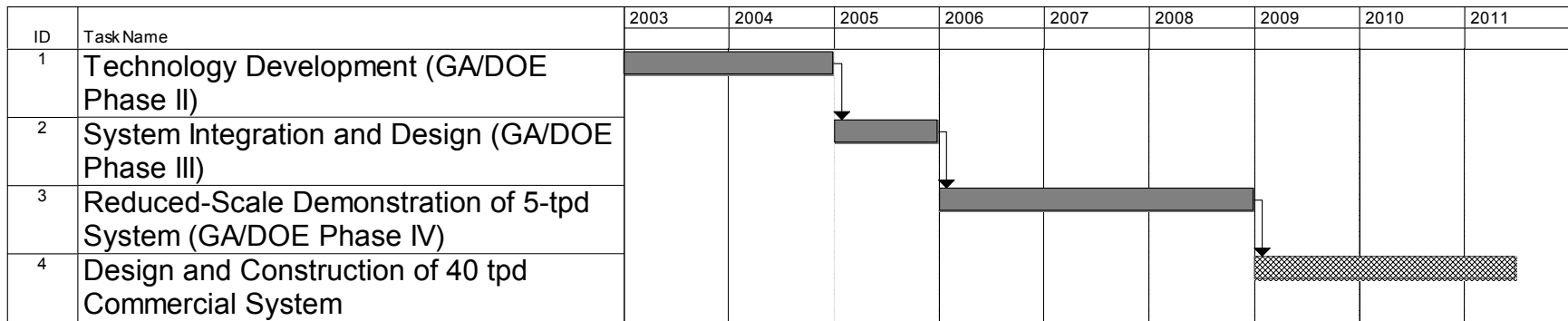
Figure C-1. Schedule for SWPO development and commercialization

PHASE II – TECHNOLOGY DEVELOPMENT

Work Scope

During Phase II, further development of SWPO technology will be performed to resolve remaining technical issues, and to establish performance requirements and system interfaces for Phase III, System Integration and Design. The technical issues requiring further development were previously discussed in Section 4. Following the scoping tests to resolve these technical issues, the GA pilot plant will be upgraded with advanced SWPO system components. Then, extended duration testing will be carried out with the key target feed, sewage sludge plus grease trap waste, to demonstrate long-term operability of the SWPO process.

Task 1 – Develop Advanced SWPO Gasification System

SWPO Scoping Tests. A number of potential process performance improvements were identified during Phase I testing that will require scoping tests early in Phase II to provide data for the design of an advanced SWPO gasification system. Each test will generally last from 4-8 hours, sufficient to acquire good quality steady state test data. The existing GA Pilot Plant will be used to perform the following series of tests:

Reduce Residual Char Formation and Increase Gasification. Reduce residual char formation and increase gasification by improving feed nozzle mixing and increasing solids residence time at temperature. Verify that the rate of char/ash buildup and removal in the reactor and heat-recovery heat exchanger are manageable. Improve pilot plant instrumentation/diagnostics to improve mass balance and yield calculations. Install an improved product gas flow instrument. Improve char collection and quantification by using straight line heat exchangers with access at both ends for routine cleaning.

Verify Gasification Yields with Target Feeds. Verify Phase I gasification yields with more representative feeds of 1) sewage sludge + trap grease, 2) micronized wood + trap grease, and 3) sewage sludge or micronized wood + micronized plastic or tire rubber. Phase I gasification yields for wood flour-ethanol feeds were generally in the range of 80-90%, with about 10-20% char and tar formation due to inadequate mixing and solids residence time. Improvements described earlier are expected to improve yields for a wide range of feeds, including sewage sludge coprocessed with grease trap waste, and other targeted feeds.

Paragraphs deleted due to proprietary content.

<u>Design, Fabrication and Installation of Advanced SWPO Gasification System.</u> As the above data for potential process improvements becomes available, decisions can be made about the preferred design for an advanced SWPO gasification system. Based on the Phase I results, it is anticipated that the advanced system will have the following characteristics:

- Downflow (or reversing flow) catalyst-free SWPO gasification reactor with internal liner enabling operation up to 800°C.

- A heat-recovery heat exchanger for preheating pumpable feeds up to 250°C.

- A pressurized catalytic reformer for conversion of methane produced in the SWPO reactor.

Paragraphs deleted due to proprietary content.

Based on the scoping tests, some or all of the above characteristics will be selected for the advanced SWPO gasification system. New components, such as the pressurized reformer, will be fabricated and installed in the pilot plant using existing hardware. Additional design modifications identified during the scoping tests will also be implemented to facilitate efficient integrated operation of the advanced SWPO gasification system during extended demonstration testing in Task 2.

Task 2 – Systematize and Test Advanced SWPO Gasification System

Once the installation of the advanced SWPO gasification system additions and modifications is complete, systemization of the integrated system will begin under Task 2. Systemization will consist of a step-wise startup and automation of the integrated system with representative feeds. Modifications to instrumentation and controls will be made as appropriate to assure robust, long-term operability.

Once systemization is complete, one or more long-term operability tests will be performed with representative feeds similar to those used in Task 1. Reliability and maintenance data will be recorded, along with the gasification data and system operating parameters. Test duration will be 50-100 hrs, with liquid and gas effluent samples taken at routine intervals throughout the tests.

Task 3 - Perform Special Studies and Update SWPO Development Plan

In parallel with the Task 1 and 2 work, several studies will be performed to accumulate relevant technical and economic data for target SWPO feedstocks and other biomass-to-energy systems for comparison to the SWPO system.

Feedstock Supply Assessment for Advanced SWPO Gasification Systems. A feedstock supply assessment will be performed to estimate the quantities of selected biomass fuels that are available for the advanced SWPO gasification system, including sewage sludge (SS), sorted municipal solid waste (SMSW), grease trap wastes, animal wastes, and potentially other (not yet identified) opportunity feeds. The focus will be primarily on feedstocks near metropolitan centers addressing supplies at various population densities.

Preliminary Economic and Market Analyses for Advanced SWPO Gasification Systems. A preliminary economic analysis will be performed to evaluate the life cycle cost of the selected advanced SWPO hydrogen gasification system. The analysis will include estimates and forecasts of biomass fuel costs, system capital, operating and maintenance costs (as provided by General Atomics), net hydrogen production costs over time, potential credits, and/or by-product revenue streams. A preliminary market analysis will be performed to better define the potential for deployment of advanced SWPO gasification systems. National and regional markets may be considered, although emphasis will be placed on California as an ideal representative market for the proposed approach.

Assessment of Biomass Gasifiers. A survey and assessment of biomass gasifiers will be performed to establish a comparative database for SWPO. The assessment will determine what gasifiers are currently or recently in operation, and will tabulate key parameters, e.g. T, P, feedstock, steam/feed ratio, hydrogen production, char formation, etc. The purpose of the assessment is to assemble performance data in a consistent format that will allow comparative analysis of different gasifiers.

Assessment of Transportation-Grade Ethanol Life Cycle Cost. Transportation-grade ethanol has become a thriving business in recent years in the United States. The corn-to-ethanol life-cycle-cost (LCC) is useful as a comparative model for other feedstocks and processing methods. An assessment of the corn-to-ethanol LCC will be performed to identify common cost drivers for other feedstocks, and to define barriers to the development biomass gasification using SWPO.

Update SWPO Development Plan. The results of these special studies will be used to update the SWPO development plan presented in the Phase I final report. The technical information from Tasks 1 and 2 will also be used in revising the development plan, and in defining the requirements for Phase III.

Schedule

Figure C-2 presents the schedule for proposed Phase II activities. Phase II start is assumed to occur January 1, 2003.

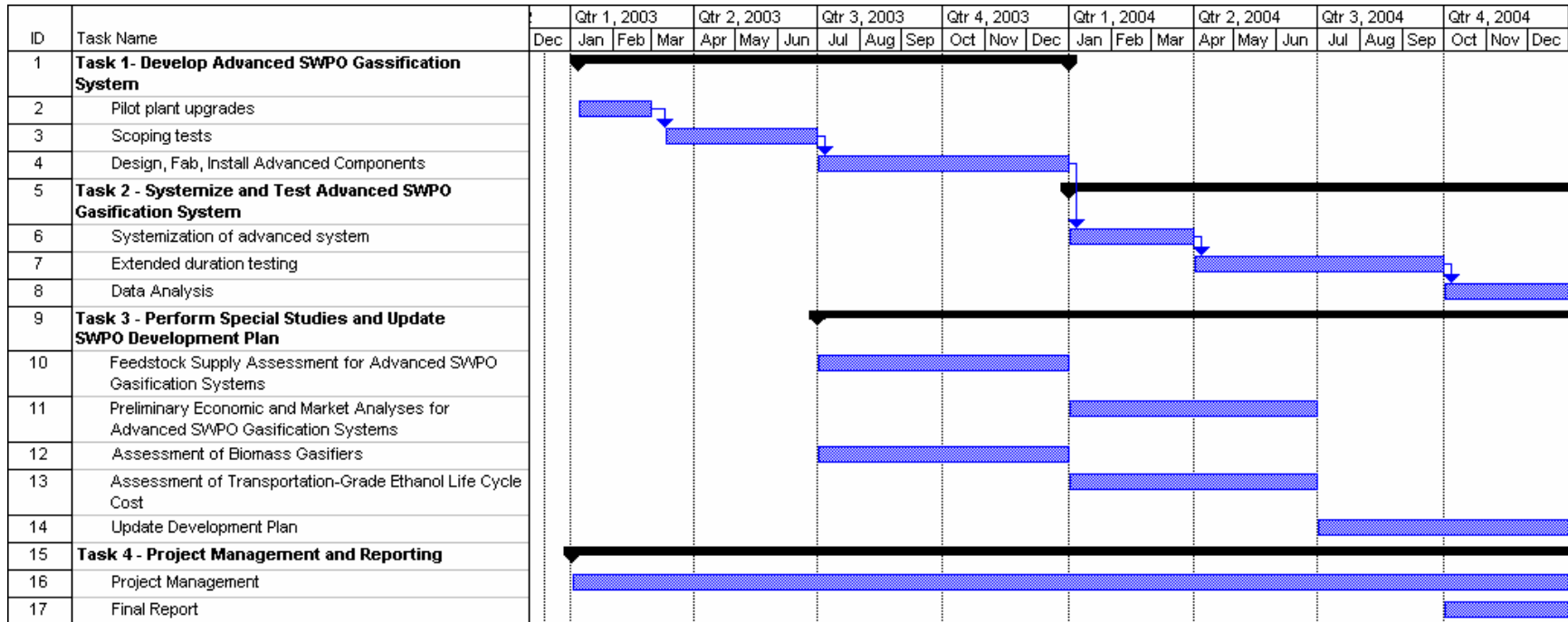| ID	Task Name	Dec	Qtr 1, 2003			Qtr 2, 2003			Qtr 3, 2003			Qtr 4, 2003			Qtr 1, 2004			Qtr 2, 2004			Qtr 3, 2004			Qtr 4, 2004		
		Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	**Task 1- Develop Advanced SWPO Gassification System**																									
2	Pilot plant upgrades																									
3	Scoping tests																									
4	Design, Fab, Install Advanced Components																									
5	**Task 2 - Systemize and Test Advanced SWPO Gasification System**																									
6	Systemization of advanced system																									
7	Extended duration testing																									
8	Data Analysis																									
9	**Task 3 - Perform Special Studies and Update SWPO Development Plan**																									
10	Feedstock Supply Assessment for Advanced SWPO Gasification Systems																									
11	Preliminary Economic and Market Analyses for Advanced SWPO Gasification Systems																									
12	Assessment of Biomass Gasifiers																									
13	Assessment of Transportation-Grade Ethanol Life Cycle Cost																									
14	Update Development Plan																									
15	**Task 4 - Project Management and Reporting**																									
16	Project Management																									
17	Final Report																									

Figure C-2. Schedule for SWPO Development Phase II.

PHASE III - SYSTEM INTEGRATION AND DESIGN

Work Scope

Phase III, System Integration and Design, involves detailed design and long-lead procurement of equipment for the reduced-scale demonstration of Phase IV, including industrial H_2 separation and storage systems. The piping and instrumentation diagram will be prepared and the process control logic developed. Equipment drawings and specifications will be prepared and procurement of long-lead equipment initiated. Supporting tasks, including a safety evaluation, RAM studies, and required permitting activities 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.

Task 1 - Systems Analyses

Perform systems analysis studies:

1. Perform safety analysis to define hazards, hazard categories and design changes required to mitigate unacceptable hazards.
2. Perform reliability, availability, and maintainability (RAM) analysis.
3. Prepare updated economic analysis.

Task 2 - System Design

Prepare 5 tpd SWPO system 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. Specify vendor-supplied equipment and components, including steam reformer, PSA, and hydrogen storage tank.
4. Define facility upgrades and support needs.
5. Prepare fabrication/installation drawings.

Task 3 - Equipment Procurement

Initiate procurement of long-lead equipment.

Task 4 – Permitting

Initiate permitting activities to install and operate the 5 tpd SWPO system at a wastewater treatment plant.

Schedule

Figure C-3 presents the schedule for proposed Phase III activities. Contract award is assumed to occur January 1, 2005.

ID	Task Name	Qtr 1, 2005			Qtr 2, 2005			Qtr 3, 2005			Qtr 4, 2005			Qtr 1, 2006		
		Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
1	**Task 1. Systems Analyses**		████████████████████████														
2	**Task 2. System Design**		████████████████████████														
3	**Task 3. Equipment Procurement**							████████████████████									
4	**Task 4. Permitting**					██████████████████████████											
5	**Task 5. Project Management and Reporting**		██														

Figure C-3. Schedule for SWPO Development Phase III.

PHASE IV – REDUCED-SCALE DEMONSTRATION OF 5 TPD SYSTEM

Work Scope

Phase IV, Reduced-Scale Demonstration of 5 tpd System, comprises a near-commercial demonstration of the integrated SWPO technology. The reduced-scale unit will process about 5 tpd of sewage sludge plus additional trap grease, approximately one-eighth the size of the commercial unit envisioned. The system will undergo shakedown and systemization testing with simple feeds. Integrated system testing with sewage sludge and grease trap waste will then be carried out over a period of several months, followed by extended testing to verify long-term operability. A successful demonstration at this scale should be sufficient to attract municipal/industrial partners for a commercial-scale demonstration.

Task 1 – Procurement

Procure remaining system components and equipment:

1. Acquire balance-of-plant equipment and materials.

Task 2 - System Assembly

Integrate the SWPO subsystems and prepare facility:

1. Assemble subsystems for integrated operation.
2. Program software for integrated operations.

Task 3 - System Checkout at GA

Testing of all system components:

1. Perform SWPO checkout tests with simulants.
2. Perform SWPO checkout tests with sewage sludge and grease trap waste.

Task 4 - Integrated Testing at Municipality

Relocate SWPO system to a municipal wastewater treatment plant, and perform extended demonstration testing, verifying economic hydrogen production and system reliability:

1. Complete required permitting.
2. Prepare municipal facility for SWPO system.
3. Install SWPO system at municipal facility.
4. Perform extended duration tests with sewage sludge and grease trap wastes.

Schedule

Figure C-4 presents the schedule for proposed Phase IV activities. Contract award is assumed to occur January 1, 2006.

ID	Task Name	2006												2007												2008												2009		
		D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M
1	**Task 1. Procurement**		▓	▓	▓	▓	▓																																		
2	**Task 2. System Assembly**			▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓																											
3	**Task 3. System Checkout**														▓	▓	▓	▓	▓	▓	▓	▓	▓																		
4	**Task 4. Integrated Testing**																										▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓				
5	**Task 5. Project Management and Reporting**		▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓			

Figure C-4. Schedule for SWPO Development Phase IV.

The survey results confirm that there are numerous potential customers with sludge disposal costs of $200/ton or more. These municipalities are ideal candidates for initial market penetration.

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., with sludge generation rates ranging from less than 5 tpd to about 150 tpd, with a median sludge generation rate of about 20 tpd (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 5 to 10 times those of sewage sludge, and serve as a future growth market requiring additional pretreatment steps and refinements for handling toxic and corrosive constituents. But these factors are again well-suited for the SWPO process. In industrialized countries worldwide, sales opportunities from just sewage sludge, pulp, and agricultural wastes number in the thousands. SWPO 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 SWPO systems. With few exceptions, they have established equipment and practices for the primary and secondary treatment of sewage sludge. However, because of continually escalating disposal costs for residual sludge solids, many plants have an ongoing interest in alternative disposal techniques. 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 an outsource agreement with a commercial contractor to operate a system 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). As confirmed by our recent market survey with SDSU, SWPO should be economically attractive for a substantial fraction of municipal treatment plants. While land application is viewed as an environmentally acceptable disposal method, concerns about low levels of pathogens and heavy metals continue to push land amendment to more rural areas.

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. None of these looms large in the current planning of wastewater treatment facility operators.

Conceivably, gasification methods other than SWPO 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. SWPO is uniquely suited to wet, dirty biomass feeds, and may be the only cost effective gasification method for low and negative value municipal wastes such as sewage sludge and grease trap wastes.

Risk

The economic analysis for SWPO of sewage sludge and grease trap waste showed favorable (even competitive) hydrogen production costs over wide ranges of key parameters, including financing during the capital cost recovery period. However, an extended time frame for payback on a first-of-a-kind technology may cause reluctance on the part of the potential users, even though similar payback periods are common for large, capital-intensive systems. In this regard, the fact that the initial customer base is the public sector may be a significant advantage. Our discussions with wastewater treatment plant personnel indicate that there is less concern with return on investment if the project meets a perceived public need. Furthermore, the stability of public entities allows access to low-rate long term financing such as bond issues.

Significant political barriers to the implementation of SWPO 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. SWPO technology has environmental advantages that will likely attract public support.

Following successful demonstration testing, SWPO 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. Financial backing will be required from 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.

Identification of Barriers and Potential Solutions

A number of potential barriers have been previously described in terms of technology development requirements. Assuming these requirements are met, there remain potential barriers with respect to displacement of existing disposal technologies with a first-of-a-kind technology with little or no prior experience. This and other 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 250,000 residents. It generates 80 tpd of digested sewage sludge solids (SSS) at 19.5% solids content (16 bone dry tons (bdt) per day) and pays about $38/wet

ton ($200/bdt) for hauling to Yuma, Arizona 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, SWPO 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 initial commercial-scale units will be installed at large existing wastewater treatment facilities with treatment capacities of 100-200 tpd of mixed SSS. The SWPO commercial-scale unit would process a side stream of 40 tpd of SSS. With this approach, should SWPO 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 SWPO technology matures, it may eventually be considered as the sole sewage sludge treatment method for new or renovated treatment works.

There are no apparent environmental barriers to the SWPO technology. Water and solid effluents from the SWPO 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 SWPO operating temperature results in minimal emissions of nitrogen oxides and sulfur oxides. By the same token, land application of treated sewage sludge solids is generally regarded as safe and environmentally acceptable for non-food crops, providing fertilization, aiding reclamation of disturbed land, and avoiding water pollution (ocean dumping) and air pollution (incineration), but requiring truck transportation and additional fossil-fuel energy consumption (see the Water Environment Federation web site at www.wef.org). Thus, SWPO is positioned as a "green" technology, with substantial environmental advantages over existing sludge disposal 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 SWPO, has been under development for more than 20 years, during which time an excellent safety record has been established. It is likely 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, there is substantial industrial experience with high temperature and high pressure processes that have excellent safety records, with growing SCW applications among them.

Marketing Plan

Sales Strategy

Sewage sludge represents a cost liability to wastewater treatment facility operators despite the well-established practices and benign or beneficial disposal methods. The focus of the SWPO

marketing effort will be to highlight the production of hydrogen and energy from sewage sludge, allowing facility operators to reduce operating expenses near-term by avoiding sewage sludge disposal costs, and lessen or eliminate long-term operating expenses related to secondary treatment of waste. Successful operation of the 5 tpd reduced-scale SWPO system at a regional wastewater facility will provide an operational data base that can be applied to the marketing effort. The reduced-scale data base will build confidence in the reliability and economic performance of commercial-scale SWPO systems and provide the necessary customer input for design of the commercial systems.

Advertising and Promotion

The near-commercial operation of the 5 tpd system at a regional wastewater facility will serve as the single most important means of promoting (through demonstration) the SWPO 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

Total estimated costs for Phases II through IV of the GA/DOE SWPO development program and the follow-on near-commercial reduced-scale demonstration are summarized in Table C-2. More detailed cost estimates will be provided at the start of each phase of the work.

TABLE C-2. BUDGETARY ESTIMATE FOR PHASES II THROUGH IV

Phase	Budget ($)
Phase II, Technology Development	1,200,000
Phase III, System Integration and Design	3,500,000
Phase IV, Reduced-scale Demonstration	2,500,000
Total for all remaining phases	7,200,000

Process Economics

Section 5.1 previously presented an economic analysis for a commercial-scale system. The economic analysis determined that a broad range of conditions exist for which SWPO can be used to produce hydrogen at competitive prices. Key factors include the following:

1. Biomass sludge credit – Sewage sludge is particularly desirable as it frequently has a negative value of $200/bdt and higher. Other biomass feedstocks are feasible if other parameters such as financing terms and availability of high heating value waste are favorable.

2. Steam credit – Steam credit is a significant offset of operating costs. Much of the steam can be available at 1200 psi if desired.

3. High heating value waste cost or credit – Grease trap waste is particularly desirable as it frequently has a negative value and is available in the same locations as sewage sludge.

4. Capital financing rate and term – Particularly favorable financing terms may be available as the customer is a municipality as opposed to a commercial entity.

5. Ratio of high heating value waste to biomass – High heating value waste leads to a higher proportion of hydrogen production.

6. Plant size – A plant treating 40 tpd of swage sludge solids is economically competitive over a broad range of conditions.

We envision that the initial commercial-scale 40 tpd SWPO system for hydrogen production can be ready for commercial deployment in approximately eight years, i.e., 2011. This assumes that all key technical issues described above have been resolved in near-commercial testing of the 5 tpd pilot plant at a wastewater treatment facility, and an initial commercial customer has been identified. Design of the 40 tpd commercial system would commence during the latter part of Phase IV, and design and construction would be completed during the subsequent commercial contract.

Technical and Financial Requirements for Manufacturing Capability

The technical requirements foreseen as necessary to achieve commercialization are essentially those described in the Development Plan of Section 5. For comparison purposes, over $200 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. Several commercial SCWO plants are currently operational for treatment of various waste streams. Several SCWO plants are expected to be built in the Government sector, as secondary treatment for waste derived from the destruction of chemical weapons.

Much of the knowledge base developed for SCWO is directly transferable to SWPO. Nevertheless it is likely that additional investments will be required to reach the point at which a wastewater entity is willing to back a first commercial plant. Phases II through IV call for over $5.5 million of GA and DOE funding. This initial investment represents a "success-oriented" estimate, i.e., it assumes that the technology development requirements are achieved and that no major obstacles are encountered and that continuing developments in SCWO will be a no-cost benefit to SWPO. In a less optimistic scenario, developmental hurdles may be encountered, and additional follow-on funding will be required. Industrial partners may be required to provide the additional funding necessary to bring the SWPO technology to commercial status.