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SUPERCRITICAL WATER PARTIAL OXIDATION

N.W. Johanson, M.H. Spritzer, G.T. Hong, W.S. Rickman
General Atomics
San Diego, CA 92121-1122

Abstract

In 2000, General Atomics was selected by DOE's Hydrogen Program to perform cooperatively-funded research on supercritical water partial oxidation (SWPO) of biomass, municipal solid waste (MSW), and high-sulfur coal to generate hydrogen. Phase I of this research is being performed in GA's privately-funded supercritical water (SCW) pilot plant at its San Diego, CA facilities.

This pilot plant is a logical next step from both the sewage sludge supercritical water gasification (SCWG) test program conducted by GA for the DOE Hydrogen Program in 1997 and the SCWG test program conducted in 1999 by GA for Environmental Energy Systems Inc. (EESI) in a cooperative program with the California Energy Commission's Public Interest Energy Research (PIER) program to successfully gasify slurries containing 40 wt% composted biomass and MSW under supercritical conditions.

SWPO involves carrying out oxidative reactions in the SCW environment – akin to high-pressure steam – in the presence of sub-stoichiometric quantities of an oxidant, typically pure oxygen or air. The key advantage of the SWPO process is the use of partial oxidation in-situ to flash heat the gasification medium through the sensitive temperature range, resulting in less char formation and improved hydrogen yields. A second advantage of the SCW process is the negligible emission of criteria pollutants, including particulates, NOx, SOx, and hazardous air pollutants. A third advantage is the high-pressure, high-density aqueous environment that is ideal for reacting and gasifying organics. The high density also allows utilization of compact equipment that minimizes capital cost and footprint requirements.

This paper provides background, describes the Phase I objectives, and discusses current status and future work.

Introduction

GA was awarded a development contract from DOE's Hydrogen Program to (a) perform a series of bench-scale Supercritical Water Partial Oxidation (SWPO) tests using cornstarch, biomass fuels, and coal, (b) perform pilot-scale design and analysis of a SWPO system concept for Phase-II development, and (c) prepare a development plan identifying cost, schedule and market potential and outlining the path forward to an integrated SWPO demonstration system.

Background

Several thermal processes exist for producing hydrogen from organic compounds. These include catalytic steam reforming, pyrolysis, plasma catalytic reforming, and supercritical water pyrolysis of wet biomass. Another thermal process for producing hydrogen is partial oxidation, whereby an organic compound is oxidized with less than stoichiometric quantities of oxygen to produce hydrogen and carbon monoxide, which then undergoes a further shift reaction with steam to convert the carbon monoxide to carbon dioxide and additional hydrogen from steam. The overall chemical reaction for the partial oxidation of methane is given by the following formula:

$$CH_4\,(g) + \tfrac{1}{2}\,O_2\,(g) \Leftrightarrow CO\,(g) + 2\,H_2\,(g)$$

The shift reaction is given by the formula:

$$CO\,(g) + H_2O \Leftrightarrow CO_2\,(g) + H_2\,(g)$$

All of these processes rely on high-temperature reactions between the organic compounds and water to produce hydrogen, carbon monoxide, carbon dioxide and methane. With the exception of the partial oxidation process, the thermal processes all require the addition of an external source of heat to drive the chemistry. The partial oxidation process gets its heat from the in-situ exothermic oxidation reactions.

Many of these processes have been adapted to the production of hydrogen from biomass with the advantage that the carbon dioxide produced will have a net zero effect on the carbon dioxide concentration in the atmosphere.

Scientific Principles of SCW Processes

SCW processes are based on the unique properties of water at conditions near and beyond its thermodynamic critical point of 705°F and 3206 psia. At typical SCW reactor conditions of 1200°F and 3400 psi, densities are only one tenth that of normal liquid water. Hydrogen bonding is almost entirely disrupted, so that the water molecules lose the ordering responsible for many of liquid water's characteristic properties. In particular, solubility behavior is closer to that of high-pressure steam than to liquid water. The loss of bulk polarity by the water phase has striking effects on normally water-soluble salts. No longer readily solvated by water molecules, they frequently precipitate out as solids.

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 1 summarizes the density and typical solubility behavior of water at 3400 psi as a function of temperature. Figures 1a and 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 Figure 1c, high-salt solutions may persist well beyond the critical temperature.

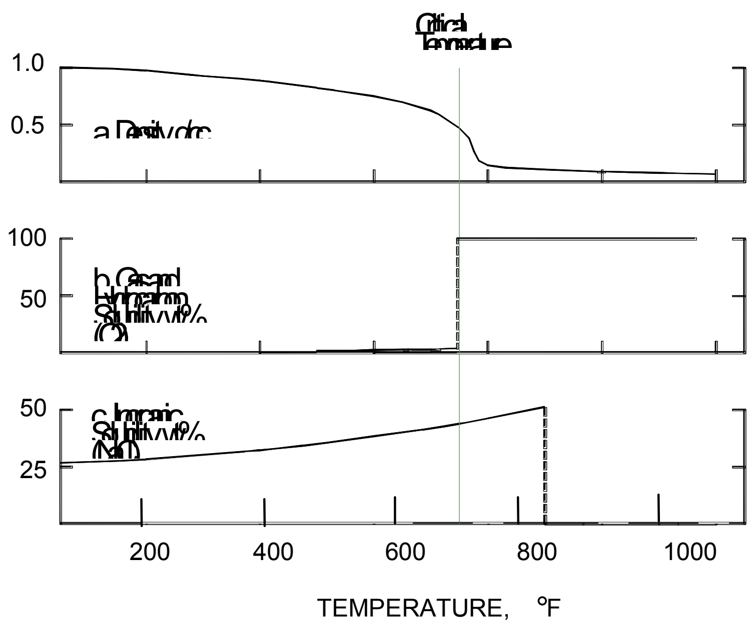

Figure 1. Characteristic of water at 3400 psi as a function of temperature.

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 reactions. Furthermore, the temperature is sufficiently high that reaction completion is usually attained within seconds to tens of seconds. Rapid reaction rates have been demonstrated for virtually all types of organic materials, including solids.

Theoretical SWPO Calculations

For the proposed SWPO process, the feed slurry can be preheated to about 752°F by heat exchange with the product stream. A mixture containing about 11% wood in water has sufficient chemical heat to raise the mixture's temperature from 752°F to 1292°F at 3400 psi, assuming all carbon converts to CO and fuel-bound hydrogen converts to water. At this temperature, the thermodynamic equilibrium for the water/CO mixture produced by the partial oxidation reaction will produce a dry gas that has about 94% hydrogen, 5% CO2, 0.3% CO, and 0.6% methane by volume after separation from the water. At 1292°F, the theoretical equilibrium yield of hydrogen in the wood to hydrogen gas is about 80%. For a 14% wood-in-water mixture at 1472°F the theoretical yield increases to 87%. These calculations assume that the quantity of wood fed to the reactor is only that required to raise the feed temperature from 752°F to the reaction temperature.

These calculations demonstrate the theoretical feasibility of producing a hydrogen-rich gas stream by utilizing partial oxidation of biomass in supercritical water. The calculations above assume all fuel-bound hydrogen converted to water. However, if the partial oxidation reaction liberates free hydrogen, as shown in first equation above, then even higher yields of hydrogen may be possible. This could be the case for an excess of fuel over the amount needed to heat the mixture to reaction temperature. This raises the first of several important technical questions that need to be resolved:

- What is the fate of fuel-bound hydrogen during partial oxidation?
- How will the actual hydrogen yield compare with theoretical calculations and does it hold promise for a commercially-viable hydrogen generation process?
- Will the oxidative "flash" heating of the feed through the char-forming temperature range suppress formation of char to acceptable levels?

Clearly, the answers will have important ramifications for the efficacy of the partial oxidation process.

Another issue is whether oxygen or air is more effective as the oxidizing agent. At SWPO reaction temperatures, the presence of nitrogen may result in ammonia formation that, if formed in sufficient quantity, could adversely impact hydrogen yield. This latter question is not one to be answered in the Phase I testing described here but should be explored during an expanded Phase II testing. Use of air will also impede the liquifaction and collection of CO_2. For the present test program the only oxidant used will be O_2.

Prior Work

There is little, if any, published data for the SWPO process in the open literature. There are a number of patents that describe partial oxidation in high-pressure steam environments. The readily-available, relevant background information and data relate to the two precursor technologies – SCWG and SCWO.

Supercritical Water Gasification (SCWG)

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). See Table 1, Summary of SCWG Test Results, below. 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. In later tests, dramatically improved results were achieved through the use of higher temperatures with reactor residence times of less than a minute. Recently, a number of results have been reported in which the yield of gas is actually higher than the mass of organic feed. This situation arises when water is consumed in gas-forming reactions.

In 1997, under sponsorship of the DOE Hydrogen Program, GA performed SCWG studies with thickened sewage sludge. At 1200°F and 2 minutes residence time, GA achieved up to 94% conversion of the sludge carbon to gas, with a small amount of char (General Atomics, 1997). In 1999, under sponsorship of the California Energy Commission's Innovations Small Grant Program, GA conducted SCWG studies for EESI using biomass comprised of sewage sludge and composted MSW (EESI/General Atomics, 2001). The primary objective was to determine the product spectrum and conversion efficiency for gasification at 3400 psig and 1200°F. Operation of the system also provided information about char formation, corrosion, and salts/solids handling. GA was able to formulate and pump heavy slurries of up to 40 wt% solids, and achieved 98% conversion of the organic carbon to gas with no char or tar formation.

Table 1. Summary of SCWG Test Results

Reference	Feedstock	%C Gasified	% H_2 Yield	Temp °F	Pressure psi	Catalyst	Reaction Time, min	Char	Scale
Modell et al., 1978	Glucose Cellulose	23 18	5 0.2	705	3200	Mixed metallic	30	None	Lab
Woerner, 1976	Maple sawdust	88	21	705	3200	None	30	None	Lab
Whitlock, 1978	Glucose	36	12	716	4750	Mixed metallic	13	None	Lab
Sealock and Elliott, 1991	Cellulose	79	NA	752	4000	Ni/Cs_2CO_3	15	None	Lab
Yu et al., 1993	Glucose	86	128	1112	5140	None	0.5	None	Lab
Xu et al., 1996	Glucose Bagasse Glycerol	99 100 100	64 56 88	1112	5140	Activated carbon Activated carbon None	0.3 1.4 0.75	None	Lab
Antal, 1996	Cellobiose Water hyacinth	100	47 31	1112	5140	Activated carbon	0.3	None	Lab
General Atomics, 1997	Sewage sludge	94	29	1200	3425	Activated carbon	2	Yes	Pilot
Antal and Xu, 1998	Corn starch (CS) Sewage sludge + CS Sawdust + CS	100 94 100	161 139 199	1200	4170	Activated carbon	0.25	None	Lab
EESI/General Atomics, 2001	Sewage Sludge + MSW	98		1200	3400	None		None	Bench

Supercritical Water Oxidation (SCWO)

SCWO has proven to be a robust method for the complete oxidation and mineralization of a wide spectrum of materials. It is particularly suited to feedstocks with a high water content, such as biomass-derived materials, as well as dirty fuels such as high-sulfur coal. It is a natural complement to the process of SCWG, with the matched pressures of the processes facilitating heat interchange.

SCWO arose as an outgrowth of the gasification work at MIT in combination with the well-known process of wet oxidation. The key concepts were formulated by Modell (1982) in the early 1980s. Experimentation quickly established that temperatures considerably higher than the critical temperature of water (705°F), in the range of 1100°F, 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 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. Residence times for complete oxidation are typically less than a minute and can be as little as several seconds for liquid or gaseous feeds. The short reaction time and relatively dense process medium results in reactors that are highly compact as compared to conventional combustors.

The effectiveness of SCWO has been demonstrated at the laboratory and pilot scale on hundreds of feedstocks. Of particular interest is sewage sludge, for which GA has carried out pilot plant development for a commercial client. The as-received sludge had a solids content of 4 to 5 wt%. Prior to SCWO treatment the sludge was treated with a thickening/dewatering agent to yield a sludge solids content up to 10.7 wt%. Processing through the SCWO unit gave organic destruction efficiencies in excess of 99%, with nondetectable SO_x and NO_x (less than 20 ppm). The solid byproduct consisted primarily of metal oxides that were shown to pass the EPA TCLP, allowing disposal in a sanitary landfill.

Other feedstocks of interest that have been treated by SCWO include 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.

Power recovery from SCWO has been a facet of interest from the very beginning of the technology (Modell, 1982). For a period of about 5 years starting in 1988, a DOE-sponsored program was carried out at Modar, Inc., with one of its goals being to evaluate the feasibility of power recovery as a byproduct from the treatment of industrial waste streams (Bettinger, 1993). The effluent gas stream was cleaned through the use of ceramic filters. A conclusion of the study was that a prototype turbine would be required to test the feasibility of operating the turbine on the cleaned supercritical stream (Stone & Webster, 1989).

Supercritical Water Partial Oxidation (SWPO)

SWPO combines elements of both fully-oxidizing SCWO (heat generation via oxidation) and fully-reducing SCWG (gas production via heat absorption). In SWPO, partial oxidation is used for rapidly heating the slurry through the transition temperature to improve the yield of hydrogen and to reduce char.

Discussion of Current Status

Phase I of the SWPO project has three major objectives:

- Bench-scale testing with heavy slurries of coal/biomass
- Pilot-scale concept design for Phase II development
- Development plan defining market fit, finance/schedule needs and the path forward to a demonstration plant

Bench-scale Tests

The start of the SWPO project was delayed to December 2000 and refocused to take advantage of the larger-scale GA-SCW pilot plant being constructed.

The SCW Pilot Plant Test Facility

The throughput of the bench-scale apparatus used for prior SCWG work was about 15 gm/min. The throughput for the SWPO test matrix in the new pilot-plant downflow reactor will in the range of 0.38 to 1.00 kg/min, a scale-up of 25 to 66 over the prior bench-top apparatus. The new pilot plant is capable of testing various process configurations and feed mixtures. Both downflow vessel and tubular reactors are installed. Feedstocks can be prepared and pumped at up to 40 wt% solids using in-line grinders/macerators and GA-developed high-pressure slurry feed pumps. Another advantage is that gaseous effluents are continuously monitored for O_2, CO_2, CO, H_2, and total HCs with an on-line gas analysis system. Figure 2 shows photographs of the general arrangement of equipment on the three major equipment skids: (1) feed skid, (2) pump skid, and (3) reactor skid.

To provide oxygen, a high-pressure oxygen supply system has been acquired and installed in an available space on the pump skid. Although air will not be tested as an oxidant for SWPO in Phase I, high-pressure air compressors are available as needed for future tests.

Figure 3 illustrates a simplified process flow diagram for the SWPO pilot plant.

Reactor skid includes preheater, scw reactors, recuperative hx's, and pressure letdown system

Pump skid supplies auxiliary fuel, feed, and quench water and gaseous oxygen

Feed skid handles liquids, slurries, and sludges

Figure 2. GA SCW Test Facility

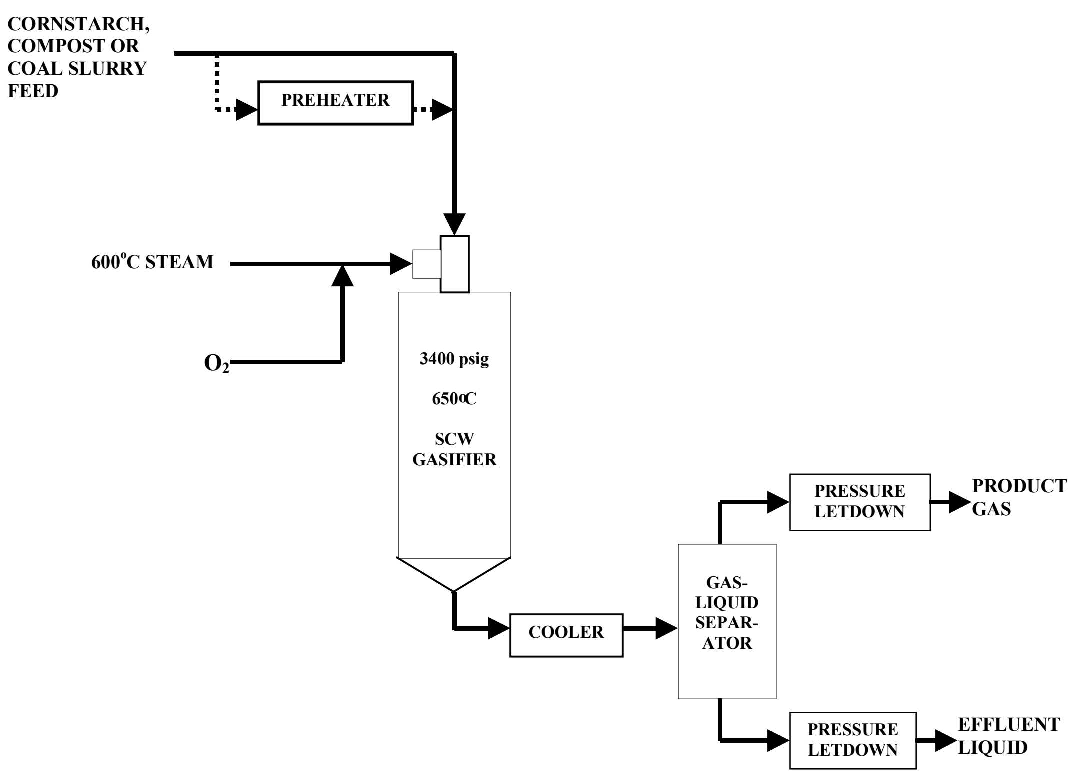

Figure 3. Simplified Process Flow Diagram for SWPO Pilot Plant

SWPO Test Plan

This Phase I test program has been structured to emphasize those feeds that have high probability of yielding significant data for evaluation of the basic partial oxidation process while requiring minimal preparation and pumping technique development. While a number of feeds were considered, it was decided to focus on those for which a high level of confidence existed that heavy slurries could be successfully prepared and fed with minimal problems. This would reduce the chance of expending effort on issues secondary to obtaining data on the core SWPO process. The three feeds selected for testing are cornstarch, composted biomass and coal.

A detailed test plan was completed including operating conditions, process measurements and instrumentation for tests of SWPO with various feedstocks. A summary of the test matrix is presented in Table 2. All tests will be conducted using the new pilot plant, which has just become available following completion of extended startup testing under General Atomics funding.

Within the budgeted time and funding we have realistically planned a total of five test series, each containing three separate test runs for a total of fifteen data points. Total test duration will be about one month.

Table 2. Test Plan Summary[(a)]

Test Seq. No.	Test Series [(b)] Ident.	Type of Fuel to be Fed	Feed Temp. (°F)	Solids Conc. (%)	Type Reactor Used	Status
-3	Start-up	Ethanol	77	0	Downflow	Complete
-2	Systemization	Cornstarch (CS)	77	0	Downflow	In Progress
-1	Systemization	Raw compost (RC)	77	0	Downflow	In Progress
1	1	CS	77	10.4 - 13.3	Downflow	Pending
2	2	CS	572	10.4 - 13.3	Downflow	Pending
3	3	Bituminous coal (BC)	77	8.0 - 13.1	Downflow	Pending
4	4	RC	77	8.0 - 13.1	Downflow	Pending
5	5	RC	572	8.0 - 13.1	Downflow	Pending
6	Optional	RC+BC (50/50)	TBD	8.0 - 13.1	Downflow	Pending
7	Optional	CS	77	10.4 - 16.5	Tubular	Pending

NOTE: (a) All tests at 1155-1200°F reactor temperature.
(b) Each test series consists of a minimum of three runs and an optional fourth run if time permits.

Each test series also allows for a fourth (optional) run should the first three runs proceed more rapidly than we expect. In addition, two additional (optional) tests series (6 and 7) are defined to be conducted only as available time permits. Under the most optimistic outcome, a total of twenty-eight data points might be obtained.

Testing will begin with SWPO tests on cornstarch. Cornstarch tests will provide a baseline for comparison to prior published data. These tests will be followed by tests with composted biomass and coal. The automated data acquisition system will record pressures, temperatures, flows, and on-line gas analyses as shown in Figure 4. Sampling and analysis will also be performed to characterize the liquid, gaseous, and solid effluents from the tests. The following test sequence will be used:

- Test Series 1 and 2 will be conducted using the model compound cornstarch in the down-flow 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 572°F prior to entering the mixing nozzle to minimize the use of oxygen and to improve the yield of hydrogen. These tests will provide SWPO data for a fuel with a relatively low C/H ratio for direct comparison to other published supercritical water gasification data.

- Test Series 3 will be conducted using coal water slurry as the feed to the down-flow reactor. These tests will provide SWPO data on fuels with very high C/H ratios.

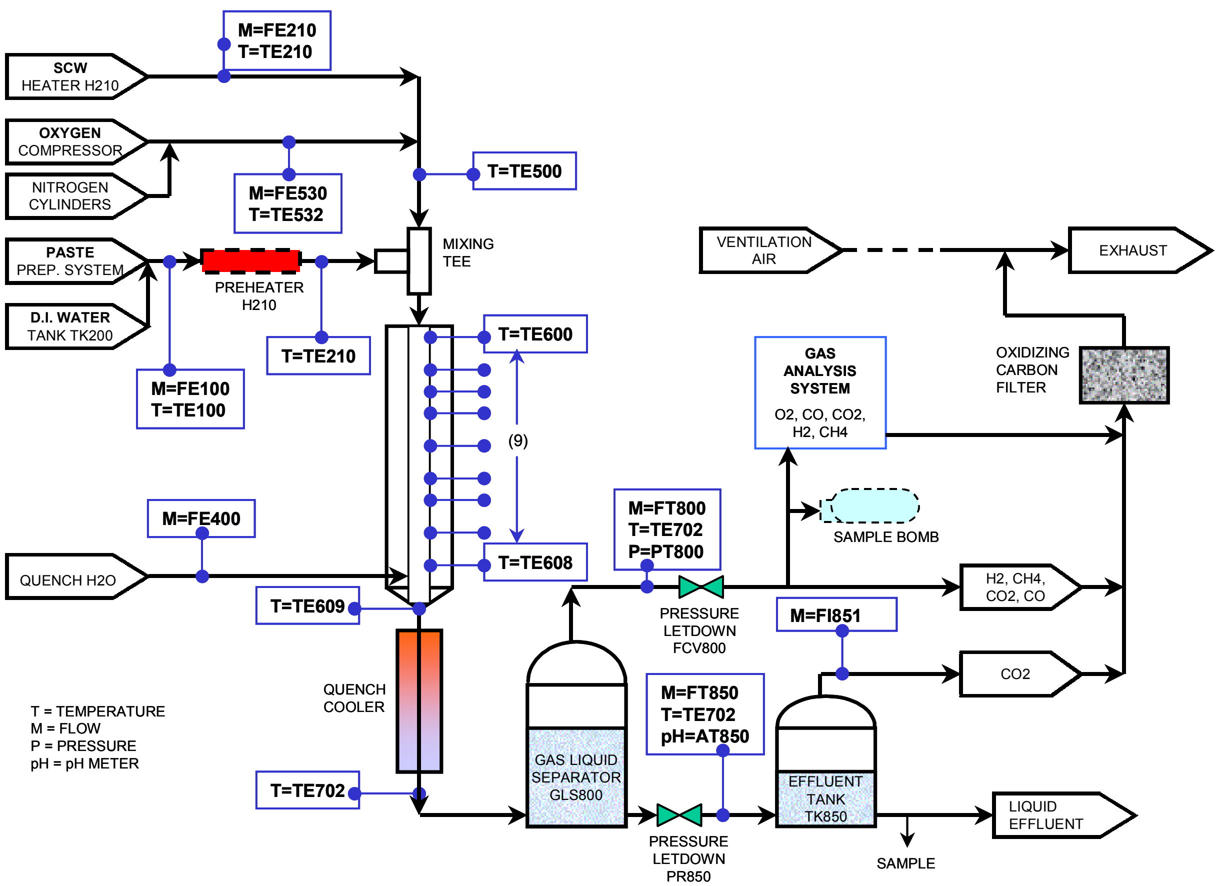

Figure 4. SWPO On-line Data Acquisition and Sampling Points

- Test Series 4 and 5 will be conducted using the raw compost in the down-flow reactor with the raw compost being heated to 572°F prior to the mixing tee in Series 5. These tests will provide SWPO data for typical biomass fuels with intermediate C/H ratios.
- 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. These tests will provide SWPO data for blended fuels with relatively high C/H ratios.
- Finally, if time permits, Test Series 7-TP will be conducted using cornstarch and the tubular reactor, at the same test conditions as Series 1. These tests will provide SWPO data for a characteristically different gasifier geometry with a relatively long residence time.

Test Progress to Date

Inventories of the three test feeds (cornstarch, composted MW/sewage sludge, and bituminous coal) were procured and are onsite. Modifications to the SCW pilot plant required for SWPO testing were completed. The high-pressure oxygen system was acquired, installed and checked out. Startup testing with ethanol was completed, but it has taken longer than originally planned to debug the system. Systemization of the pilot plant is currently underway, with integrated runs using compost slurry and cornstarch. These tests will complete the startup/systemization phase and confirm pilot-plant readiness for the SWPO test plan matrix.

Pilot-scale Design/Analysis

This task has two main subtasks: Conceptual Design and System Engineering Analysis.

Pilot-scale Conceptual Design

Considerable progress has been made on the conceptual design of the SWPO pilot-scale system. A detailed six-sheet P&ID has been prepared for the SWPO configuration of the new pilot plant that incorporates most of the expected features of the SWPO process for Phase II development.

System Engineering Evaluation

The preliminary integrated SWPO system design is being evaluated to identify potential interface components through literature reviews, survey of equipment vendors, as well as a review of prior gasification work and system integration studies performed by GA. Review of the most recent developments forthcoming from the DOE Hydrogen Program are also being factored into this evaluation.

The block flow diagram, Figure 5, defines the key steps in an overall process of converting biomass or low-grade fuels into hydrogen suitable for a variety of end-uses. Emphasis is on the SWPO core technologies that the subject of development for this multi-phase project (see Future Work). Feed preparation and gas cleanup and separation requirements remain to be defined.

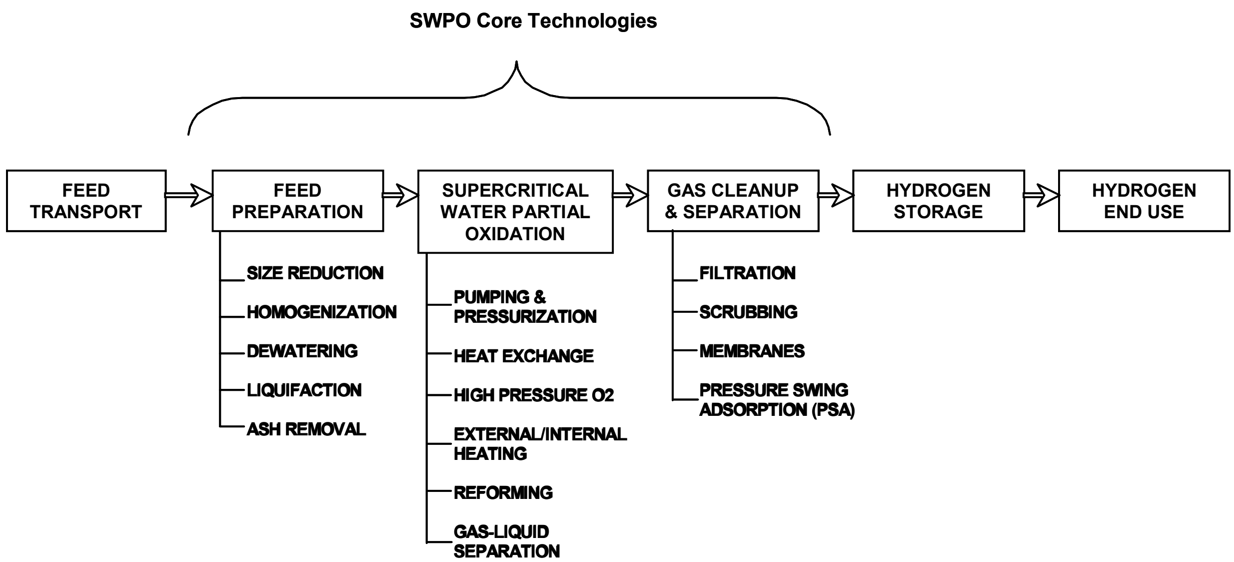

Figure 5. Block Flow Diagram for an Integrated SWPO Hydrogen System

A preliminary review of the technology associated with each of the major components and subsystems for the steps identified in Figure 5 is underway. Based on this preliminary review, the principal development requirements are summarized in Table 3. The items requiring substantial further development are shown in bold-face type. This evaluation is continuing and will likely change as the SWPO data becomes available.

Table 3. Summary of Development Requirements for Component Technologies

Component Technology	Status
Feed particle size reduction	Commercially available with minor modifications
Sludge Pretreatment	Unnecessary for many feeds, more development required for others
High pressure slurry pumping	Commercially available
Heat exchange/recovery	Some testing at lab and pilot scale; more development needed
Pure O_2 or high O_2 content oxidant	Commercially available
SCWO and SCWG Reactors	Some testing at lab and pilot scale; more development needed
Gas-liquid separation	Development essentially complete
Gas cleanup/separation	Some commercially available, others tested at lab and pilot scale; more development needed

SWPO Development Plan

A development plan is being prepared for the commercialization of SWPO for the production of hydrogen/hydrogen-rich fuel gases from biomass and low-grade fuel. This task encompasses three subtasks: Cost and Schedule Estimate, a Business Plan identifying SWPO/H_2 market potential, and Definition of Follow-on Activities leading to an integrated SWPO demonstration system.

The commercial software BizPlan Builder is being used to create the plan for commercializing the integrated SWPO pilot-scale demonstration system. BizPlan incorporates a series of central topic templates that include Product Strategy, Market Analysis, Marketing Plan and Financial Plan. The templates may be tailored to the specific needs of the development plan for the SWPO technology.

The SWPO plan will be developed along parallel lines used by Mann (1995) to evaluate the BCL gasifier and will make use of prior analysis of a SCWG system for gasification of biomass (General Atomics, 1997).

Development Cost/Schedule

The development plan incorporates specific plans for the pilot-scale development effort, including the detailed design and fabrication of the SWPO unit operation as well as slurry feed preparation and pumping equipment, heat exchange equipment and gas conditioning equipment. Cost and schedule estimates will be prepared for pilot-scale demonstration and follow-on phases of development.

Business Plan Identifying SWPO Market Potential

A business plan is also in preparation. The business plan evaluates the market potential for the SWPO technology including economic analysis to provide comparisons with other conventional or advanced hydrogen generation methods. Elements being considered in the market analysis are market definition, customer profiles, competition for feed stocks, financial risk, promotion and sales strategy.

Ongoing market explorations include discussions with municipal authorities to determine the generation rates, characteristics and variability of potential biomass feed stocks and to determine the incentives that will create interest in cooperative partnerships. One local authority, the San Diego Municipal Waste Water Department (MWWD) and the Environmental Services Department (ESD) have expressed interest in the possibility of being a host site for a demonstration pilot-scale SWPO plant. The MWWD and ESD have co-located facilities for sewage sludge collection and municipal solid waste sorting, recycle, and landfill. These are the targeted feedstock for GA’s SWPO technology, and a summary of the available feedstock quantities for San Diego is provided in Table 4. The items in bold-face type are the most likely sources of SWPO biomass feedstocks. These categories total about 500,000 tons of moisture-containing biomass, or about 250,000 dry tons per year.

Follow-on Activities Leading to Pilot-Scale Demonstration of Integrated SWPO System

Detailed activities that must be implemented in order to move the SWPO technology forward from bench-scale testing to an operational integrated demonstration plant will be laid out in the development plan. The required steps to mature the technology will be structured into a multi-phased, multi-year schedule with well-defined critical progress milestones.

A proposal for the Phase II follow-on work is underway for submittal in June 2001.

Table 4. San Diego Annual Materials Disposed by Major Sectors[a]

Material Type	Residential Waste Generated In-City Est. Pct.	Est. Tons	Commercial Waste Generated In-City Est. Pct.	Est. Tons	In-City Military Facilities Est. Pct.	Est. Tons	City Departments Est. Pct.	Est. Tons
Recyclable Paper	23.0%	137,099	15.0%	115,976	10.6%	10,793		
Rock, Soil and Fines			8.0%	62,291	29.7%	30,310	25.6%	53,553
Food	13.9%	82,911	6.6%	51,379	5.4%	5,465		
Sewage Solids							**57.7%**	**120,560**
Recyclable Yard Waste	**13.4%**	**79,934**	**4.7%**	**36,194**				
Treated Lumber	**3.2%**	**18,852**	**7.0%**	**53,888**	**16.4%**	**16,695**		
Remainder/Composite Paper	**6.8%**	**40,243**	**5.2%-**	**39,913**				
Concrete	3.0%	17,633	5.5%	42,964	3.1%	3,157		
Non-Treated Lumber			**6.5%**	**50,455**	**4.1%**	**4,218**		
Film Plastic	**3.5%**	**20,945**	**3.1%**	**24,238**				
Carpet & Carpet Padding			5.3%	41,087				
Gypsum Board			4.7%	36,240				
Asphalt Roofing			4.3%	33,570				
Other Ferrous Metal			3.8%	29,642	3.5%	3,537		
Remainder/Composite Construction and Demolition			3.9%	29,888				
Contaminated soil, street sweepings, drain cleanings					3.6%	3,689	6.9%	14,380
Asphalt Paving							3.3%	6,836
Subtotal	**66.8%**	**397,617**	**83.7%**	**647,724**	**76.3%**	**77,865**	**93.4%**	**195,329**
All Other Waste Types	33.2%	197,212	16.3%	126,571	23.7%	24,187	6.6%	13,706
Total Disposed	**100.0%**	**594,829**	**100.0%**	**774,295**	**100.0%**	**102,052**	**100.0%**	**209,035**

[a](City of San Diego, 2000)

Concurrent and Related Activities

Efforts in addition to Phase I objectives include actively pursuing related programs with both NETL and with the California Energy Commission's P.I.E.R. program to broaden the funding base for development of SWPO and related SCW technologies.

GA is actively pursuing strategic partnerships, contracts with related programs, and other opportunities to advance the technology. In March, GA presented a technical paper on supercritical water cycles at the 26th International Technical Conference on Coal Utilization & Fuel Systems. (March 5-8, 2001 in Clearwater, FL). In May, GA submitted a Memorandum of Understanding to the City of San Diego to form an alliance directed toward the joint development of biomass power generation based on municipal wastes.

Future Work

The future path beyond Phase-I and the probable time-line leading to a SWPO demonstration plant is outlined below in the following phases.

- Phase II: Technology Development: (1/02 to 12/03)
  - Design, fabricate and test pilot-scale SWPO reactor
  - Optimize SWPO operating parameters and hydrogen yields
  - Demonstrate feasibility; provide data for evaluation and scale-up

- Phase III: System Integration and Design: (1/04 to 12/04)
  - Safety, reliability and maintainability analyses
  - Life-cycle cost analyses
  - Process design and long-lead procurement for Phase IV

- Phase IV: Demonstration Plant: (1/05 to 12/07)
  - Implement requirements defined during Phase III studies
  - Match pilot-scale SWPO to industrial hydrogen separation and storage systems

Each of these future phases will be expanded and detailed as a part of the development plan being prepared in Phase I.

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