Fuel-Flexible Gasification-Combustion Technology for Production of H_2 and Sequestration-Ready CO_2

Quarterly Technical Progress Report No. 3

Reporting Period:

April 1, 2001 – June 30, 2001

George Rizeq, Janice West, Arnaldo Frydman, and Vladimir Zamansky (GE EER)
Linda Denton, Hana Loreth, and Tomasz Wiltowski (SIU-C)

July 2001

DOE Award No. DE-FC26-00FT40974

General Electric Energy and Environmental Research Corporation
(GE EER)
18 Mason
Irvine, CA 92618

DISCLAIMER

"This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof."

ABSTRACT

It is expected that in the 21st century the Nation will continue to rely on fossil fuels for electricity, transportation, and chemicals. It will be necessary to improve both the thermodynamic efficiency and environmental impact performance of fossil fuel utilization. General Electric Energy and Environmental Research Corporation (GE EER) has developed an innovative fuel-flexible Advanced Gasification-Combustion (AGC) concept to produce H_2 and sequestration-ready CO_2 from solid fuels. The AGC module offers potential for reduced cost and increased energy efficiency relative to conventional gasification and combustion systems. GE EER was awarded a Vision-21 program from U.S. DOE NETL to develop the AGC technology. Work on this three-year program started on October 1, 2000. The project team includes GE EER, California Energy Commission, Southern Illinois University at Carbondale, and T. R. Miles, Technical Consultants, Inc.

In the AGC technology, coal/opportunity fuels and air are simultaneously converted into separate streams of (1) pure hydrogen that can be utilized in fuel cells, (2) sequestration-ready CO_2, and (3) high temperature/pressure oxygen-depleted air to produce electricity in a gas turbine. The process produces near-zero emissions and, based on preliminary modeling work in the first quarter of this program, has an estimated process efficiency of approximately 67% based on electrical and H_2 energy outputs relative to the higher heating value of coal. The three-year R&D program will determine the operating conditions that maximize separation of CO_2 and pollutants from the vent gas, while simultaneously maximizing coal conversion efficiency and hydrogen production. The program integrates lab-, bench- and pilot-scale studies to demonstrate the AGC concept.

This is the third quarterly technical progress report for the Vision-21 AGC program supported by U.S. DOE NETL (Contract: DE-FC26-00FT40974). This report summarizes program accomplishments for the period starting April 1, 2001 and ending June 30, 2001. The report includes an introduction summarizing the AGC concept, main program tasks, objectives of this program, and provides a summary of program activities covering program management and progress in first year tasks including lab- and bench-scale design, facilities preparation, and engineering studies.

TABLE OF CONTENTS

INTRODUCTION

Electricity produced from hydrogen in fuel cells can be highly efficient relative to competing technologies and has the potential to be virtually pollution free. Thus, fuel cells may become an ideal solution to many of this nation's energy needs if one has a satisfactory process for producing hydrogen from available energy resources such as coal, and low-cost alternative feedstocks including biomass, municipal solid waste, sewage sludge, and others.

This Vision-21 program addresses a novel, energy-efficient, and near-zero pollution concept for converting a conventional fuel (coal) and opportunity fuels (e.g., biomass) into separate streams of hydrogen, oxygen-depleted air, and sequestration-ready CO_2. This concept is referred to throughout this report as *Advanced Gasification-Combustion (AGC)*. When commercialized, the AGC process may become one of the cornerstone technologies to fulfill Vision-21 energy plant objectives of efficiently and economically producing energy and hydrogen with utilization of opportunity feedstocks.

The AGC technology is energy efficient because a large portion of the energy in the input coal leaves the AGC module as hydrogen and the rest as high-pressure, high-temperature gas that can power a gas turbine. The combination of producing hydrogen and electrical power via a gas turbine is highly efficient, meets all objectives of Vision-21 energy plants, and makes the process flexible. That is, the AGC module will be able to adjust the ratio at which it produces hydrogen and electricity in order to match changing demand.

The three-year Vision-21 AGC program will be conducted primarily by General Electric Energy and Environmental Research Corporation (GE EER) under a Vision-21 contract from U.S. DOE NETL (Contact No. DE-FC26-00FT40974). Other project team members include Southern Illinois University at Carbondale (SIU-C), California Energy Commission (CEC), and T. R. Miles, Technical Consultants, Inc. The AGC project integrates lab-, bench- and pilot-scale studies to demonstrate the AGC concept. Engineering studies and analytical modeling will be performed in conjunction with the experimental program to develop the design tools necessary for scaling up the AGC technology to the demonstration phase. The remainder of this section presents objectives, concept, and main tasks of the AGC program.

Program Objectives

The primary objectives of the AGC program are to:

- Demonstrate and establish the chemistry of the AGC concept, measure kinetic parameters of individual process steps, and identify fundamental processes affecting process economics.
- Design and develop a bench- and pilot-scale systems to test the AGC concept under dynamic conditions and estimate the overall system efficiency for that design.
- Develop kinetic and dynamic computational models of the individual process steps.
- Determine operating conditions that maximize separation of CO_2 and pollutants from vent gas, while simultaneously maximizing coal/opportunity fuels conversion and H_2 production.
- Integrate the AGC module into Vision-21 plant design and optimize work cycle efficiency.
- Determine extent of technical/economical viability & commercial potential of AGC module.

AGC Concept

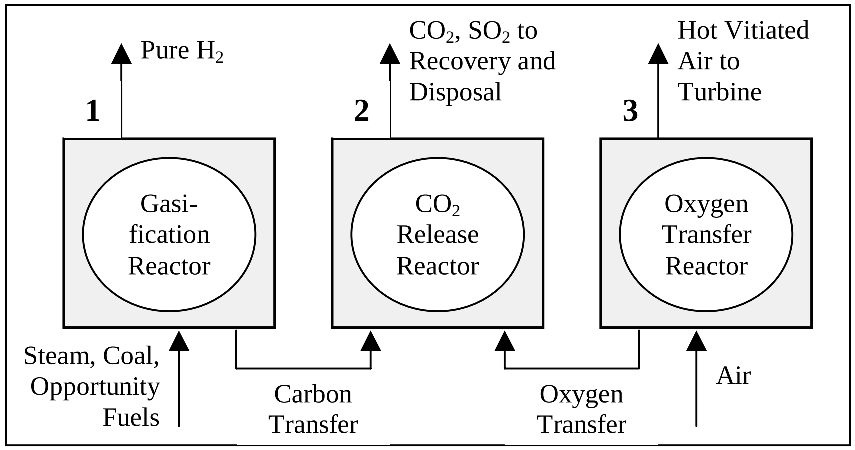


Figure 1. Conceptual design of the AGC technology.

Figure 1 shows the conceptual design of the AGC technology where three reactors are used. In Reactor 1, coal and opportunity fuels (5-10% by heat input) are gasified by steam in the presence of a CO_2-absorbing bed material. As CO_2 is scavenged, CO is also depleted from the gas phase due to the water shift reaction. Consequently, mainly H_2 is released from Reactor 1. Only part of the solid fuels fed to Reactor 1 is gasified to produce hydrogen. The remaining char and bed material are transferred to Reactor 2 where the carbon is oxidized to supply the thermal energy necessary to regenerate the CO_2-absorbing bed material and release CO_2 as shown in Figure 1. Oxygen-transfer bed material is moved from Reactor 3 to Reactor 2 to provide the oxygen necessary to oxidize the char in Reactor 2, in turn raising the bed temperature for decomposition and release of CO_2. Air is supplied to Reactor 3 to regenerate the oxygen-transfer bed material. Coming out of Reactor 3, the hot oxygen-depleted air passes to a gas turbine to generate electricity and the hot bed materials return to Reactor 2. Ash and some bed material will be removed from the system periodically to reduce the amount of ash in the reactor and to replenish the bed materials with fresh compounds.

Project Plan

The tasks planned for the AGC project are summarized in Table 1. These tasks will be conducted over the three-year period that started October 1, 2000. Success of the AGC program depends on the efficient execution of the various research tasks outlined in Table 1 and on meeting the program objectives summarized above.

Table 1. Main tasks of the AGC program.

Task	Task Description
Lab-Scale Experiments – Fundamentals *Task 1*	Design & assembly Demonstration of chemical processes Sulfur chemistry
Bench-Scale Test Facility & Testing *Tasks 2 & 3*	Bench test facility design Subsystems procurement & assembly Bench test facility shakedown Reactor design testing Parametric evaluation Fuel-flexibility evaluation Pilot operation support
Engineering & Modeling Studies *Task 4*	Opportunity fuels resource assessment Preliminary economic assessment Kinetic & process modeling Integration into Vision-21 plant Pilot plant control development
Pilot Plant Design, Assembly, & Demonstration *Tasks 5, 6, & 7*	Process design Subsystems specification/procurement Reactor design & review Reactors manufacture Components testing Pilot plant assembly Operational shakedown modifications Operational evaluation Fuel-flexibility evaluation Performance testing
Vision 21 Plant Systems Analysis *Task 8*	Preliminary Vision-21 module design Vision-21 plant integration Economic & market assessment
Project Management *Task 9*	Management, reporting, & technology transfer

PROGRAM PLANNING AND MANAGEMENT

In addition to the technical activities conducted in this program, regular project management functions were performed during this quarter, including assessment of resources and personnel needs, monitoring spending versus that allocated in the budget, and following-up project progress versus goals. In the third quarter, a new Ph.D.-level chemical engineer was hired for this program, and other staffing issues were resolved, allowing accelerated progress, especially in the Task 2 activities. One additional engineer is expected to join the program in the upcoming fourth quarter.

A project review meeting was held at GE EER's Irvine office on June 4, 2001, where key SIU-C Vision 21 AGC Project team members provided updates on the lab-scale activities (Task 1). The presentations focused on their most recent work on the cold-flow fluidization study and plug-flow reactor testing.

A mid-year review meeting was held with the Vision-21 team and GE EER's president/CEO as well as other senior management personnel on June 15, 2001. The meeting was successful, and attendees provided valuable comments on both the program progress and the future direction of AGC technology development.

In this program, technology transfer is also planned through attending professional conferences and meetings, and presenting ongoing results from the AGC project. A paper that will be presented at the 11th ICCS in San Francisco (Sept. 30- Oct. 5, 2001) was submitted to the conference coordinators at NETL by its June 29,2001 due date.

EXPERIMENTAL ACTIVITIES AND RESULTS

Experimental activities currently in progress are primarily concerned with the preparation of experimental facilities for both Task 1 laboratory-scale and Task 2 bench-scale AGC systems. Progress has been made in the design and construction of these two facilities. The reactor and furnace have been constructed at SIU-C, and the bench-scale system is near completion, with shakedown testing underway at GE EER's test site in Irvine, CA.

Laboratory-Scale (Task 1) Activities

The primary objective of Task 1 is to perform a laboratory-scale demonstration of the individual chemical and physical processes involved in the GE EER fuel-flexible AGC technology. This task is primarily being conducted by SIU-C.

Work conducted in the third quarter has involved:

- Construction and testing of a furnace for the lab-scale test facility,
- Cold-flow modeling to identify key fluidization factors for the bed materials to be used in the program, and
- Plug-flow reactor testing at 800°C to study the effectiveness of the bed materials in absorbing and desorbing CO_2.

Lab-Scale Furnace

A furnace, designed to heat the fluidized bed reactor to temperatures of 1000°C, was designed, built and tested. Ni-Cr 80-coiled heating elements were cast into ceramic refractory using a sheet metal mold. Dimensions of the furnace assured a three-inch space between the exposed nickel-chromium wire and the stainless steel reactor. Refractory thickness was three inches and the exterior of the sheet metal mold was allowed to remain attached to the cured ceramic as a stabilizing shell. Ports were added for thermocouples, gas inlets and gas outlets.

Electrical control of the furnace was attained through use of microprocessor-based controllers from Omega (model CN 76153), with current output. Three-phase zero-crossing switches (Omega Engineering Model #SCR73Z-230) were used with a 220-volt line supply. The heating elements were wired in a Y-configuration to limit the current to each of the three branches in each furnace half. A third safety controller/thermocouple combination was added to prevent runaway heating.

Upon initial testing, the furnace easily reached 500°C, with the inside temperature of the reactor reaching 450°C within three hours. However, three heating elements burned out upon reheating the next day. Inspection revealed a shifting of the coils during casting. The resulting hot spots were responsible for the open circuit. The broken wires were removed and replaced, with new refractory applied to hold them in place. As a precaution, all refractory was removed from the face of the heating coils to prevent excessive heat retention near the wire.

After a suitable curing time, the furnace temperature was gradually raised to 500°C, then 700°C, with no major problems. After an overnight cool-down, the temperature was again raised gradually to 700°C, when the center element of the right half of the furnace burned out. The temperature of the left half of the furnace reached 800°C before the center element in that section burned out. The furnace was rewired and tested for temperature control and ramp rate. An operating temperature of 800°C was achieved inside the reactor in approximately 4½ hours, with less than 50°C heating difference between the two furnace halves at any time during the heat-up. Controllers and heating elements performed within specs.

One set of mica gaskets was used to seal the reactor, along with eight Incoloy bolts torqued at 80 foot-pounds. The reactor was held at 817°C and the furnace halves at 797°C for 50 minutes at atmospheric pressure. No oxidation of the mica sealant was observed upon visual inspection of the gaskets and reactor faces after cool-down.

At present, pressure tests are being used to identify leaks in welds and connections of the ports and delivery system. When this is completed, a second set of gaskets will be used for high-temperature, high-pressure tests.

Cold-Flow Modeling

SIU-C also performed a study to help identify fluidization conditions of the reactors. Cold-flow modeling and correlation-based predictions were used to estimate key fluidization factors for the bed materials. A detailed description of the tests conducted and the results obtained is provided in Appendix A.

Plug Flow Reactor (800°C)

SIU-C initiated cyclic experiments in order to sequentially investigate the reactions in the reactor and regenerator. Typically, experiments were conducted over 5 cycles by alternately feeding CO and air over a catalyst bed of CO_2-absorption material (CAM) and oxygen-transfer material (OTM). The purpose of the tests was to determine how many cycles the materials could withstand before significant deactivation occurred. Figure 2 shows CO_2 measurements as a function of time. The best performance, in terms of lowest concentration of CO_2 in the outlet gas, was observed for a CAM/OTM mixture with particle sizes of around 45 micrometers.

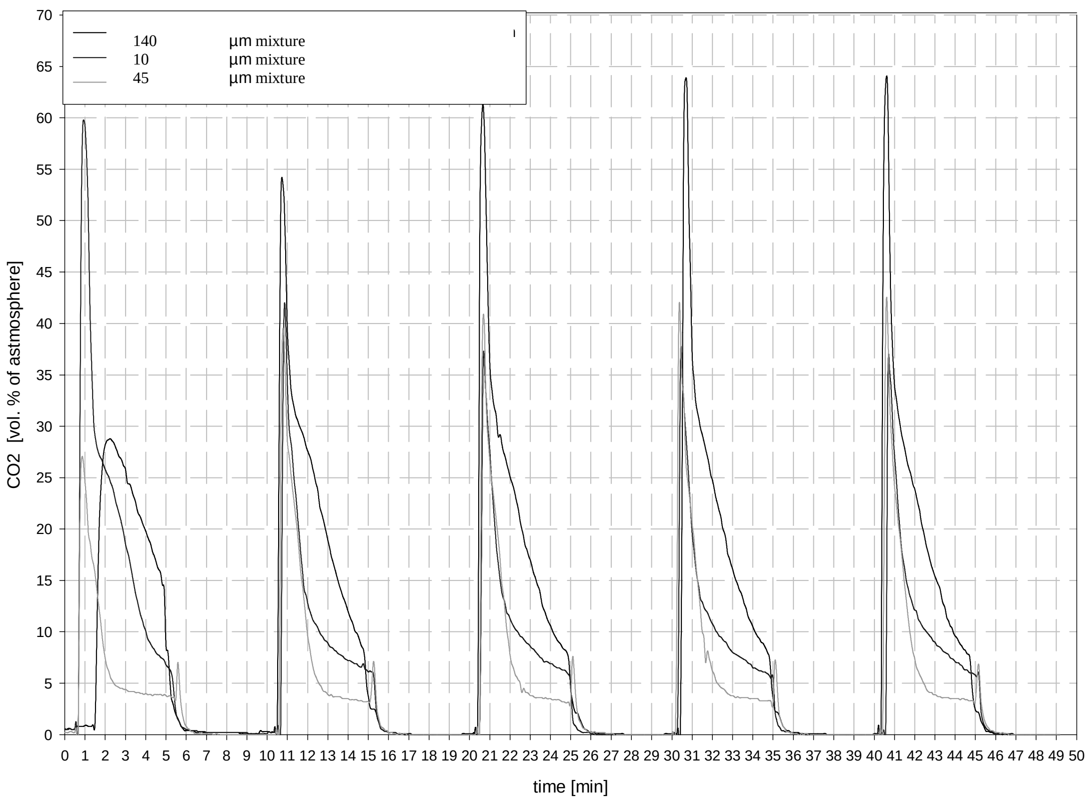


Figure 2. Plug flow results, comparison of mixtures of CAM and OTM.

Bench-Scale Facility (Task 2) Activities

The objective of Task 2 is to design, assemble and shakedown the bench-scale experimental facility. Work conducted in this quarter has focused on the assembly and construction of the bench-scale test facility and optimization of the reactor design.

System Design

The bench-scale test facility has been constructed and shakedown testing has been initiated on several of the subsystems. An updated detailed process and instrumentation diagram (P&ID) is shown in Figure 3. This diagram shows the tag numbers for each system component. Table 2 is a list of tag numbers (as shown on the P&ID) along with parts specification information. The reactor is depicted at the center of the P&ID diagram of Figure 3.

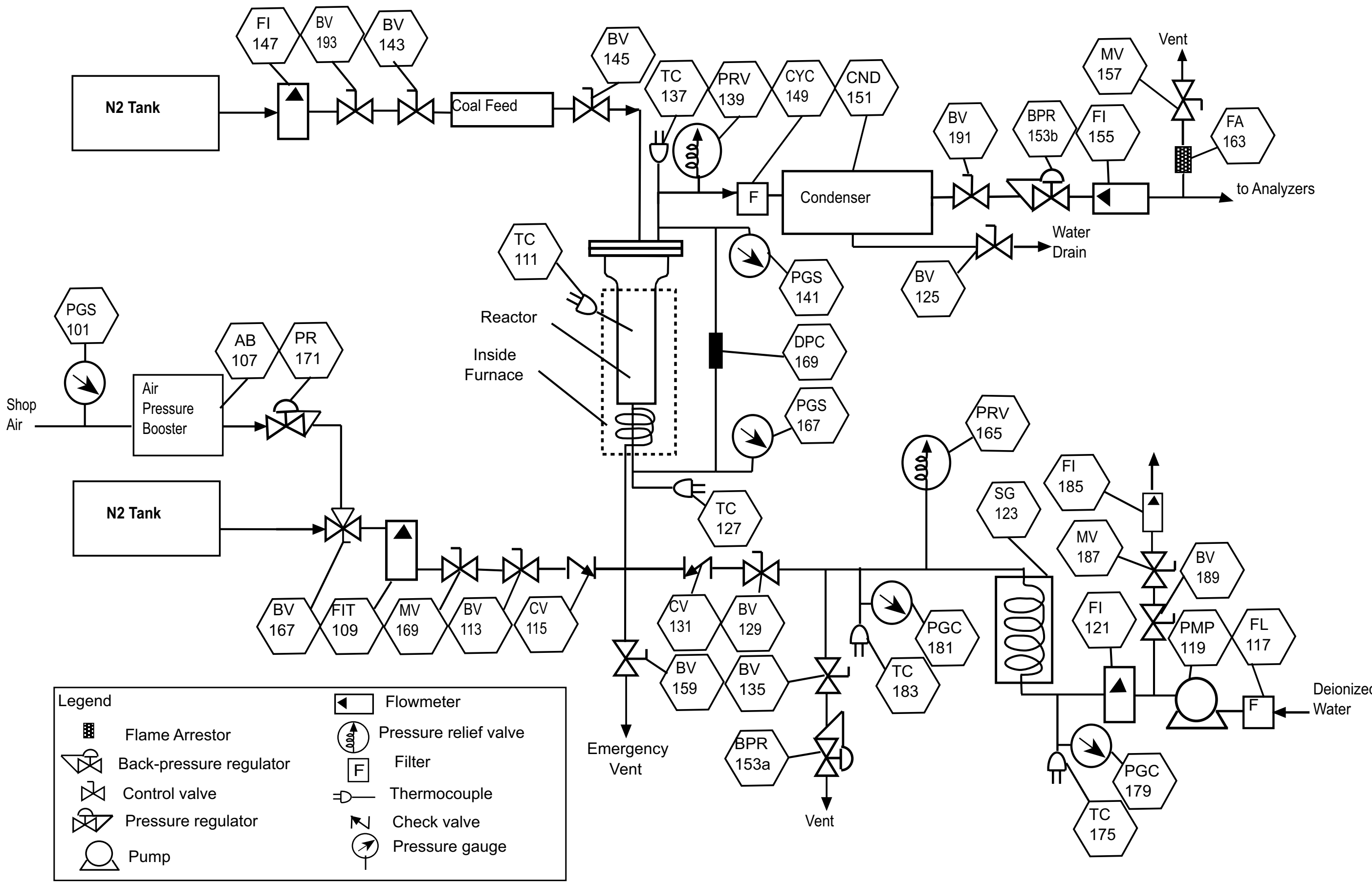


Figure 3. Process and Instrumentation Diagram (P&ID) for bench-scale system.

Significant progress has been made on the following aspects of the system:

- Steam feed system
- Air/N_2 feed system
- Coal delivery system
- Product gas conditioning and analysis
- Control system
- Data acquisition system

Steam feed system

The steam feed system has been specified and is currently being assembled. A pump will be used to provide water at high pressure to a preheating coil located in an electric furnace. When steam is not being fed to the reactor (BV 129 is closed), excess steam pressure will be vented via back-pressure regulator 153a (BV135 will be open), allowing the steam feed system to operate continuously, preventing steam condensation in the feed lines and facilitating a simple transition between nitrogen and steam feeds. Instrumentation is available to monitor the temperature and pressure of the steam both before and after the steam preheater coil.

Table 2. Parts list with tag numbers.

Tag Number	Part Description	Service Desciption	Max Pressure	Temp	Flow Range	Pressure Range	Cracking Pressure	Line Size	Cv
AB107	Air Pressure Booster	Compressed Air	350psi	ambient	10-100 scfh	100-500psi		1/2" npt	
AD105	Air Dryer	Compressed Air	150psi	ambient	10-100 scfh			3/4" npt	
BPR153	Back Pressure Regulator	Analyzer Vent	350 psi	500F	10-200 scfh	10-350psi		1/2"npt	0.5-3
BV113	Ball Valve, Actuated		350 psi	ambient				1/4" tube	0.2-1
BV129	Ball Valve, Actuated	Steam	350 psi	500F				1/4" tube	0.2-1
BV143	Ball Valve,Actuated	Coal Feed	350 psi	ambient				1/4" tube	0.2-1
BV145	Ball Valve,Actuated	Coal Feed	350 psi	ambient				1/4" tube	0.2-1
BV167	Ball Valve, Actuated, 3-Way	Air/N2	350psi	ambient				1/4" tube	0.2-1
BV159	Ball Valve, Actuated	Emergency Vent	350psi	500F				1/4" tube	0.2-1
*CND151	Condenser	Analyzers						3/8" tube	
CV115	Check Valve		350 psi	ambient			1-3psi	1/4" tube	
CV131	Check Valve		350 psi	500F			1-3psi	1/4" tube	
DPC169	Differential Pressure Transducer	Reactor Pressure	350 psi	500F		1-350psi		1/4" tube	
FA163	Flame Arrestor	Product	350psi	500F				1/4" tube	
FI109	Flow indicator	Compressed Air	350 psi	ambient	10-100 scfh			1/4" tube	
FI121	Flow indicator	D.I. Water	350 psi	ambient	5-75 ml/min (.08-1.2 gal/hr)			1/4" tube	
FI147	Flow indicator	Coal Feed	350 psi	ambient	10-100 scfh			1/4" tube	
FI155	Flow indicator	Analyizers	100 psi	ambient	10-200 scfh			1/4" tube	
FL103	Air Filter	Compressed Air	150 psi	ambient				3/4" npt	
FL117	Filter	D.I. Water	150 psi	ambient				1/2" npt	
MV157	Metering Valve	Analyzers	150 psi	ambient	10-200 scfh			1/4" tube	0.2-1
MV169	Metering Valve	Analyzers	150 psi	ambient	10-200 scfh			1/4" tube	0.2-1
MV177	Metering Valve	Analyzers	150 psi	ambient	10-200 scfh			1/4" tube	0.2-1
PG141	Pressure Gauge	Reactor Product	350 psi			0-500 psi		1/4" npt	
PG167	Pressure Gauge	Reactor Supply	350 psi			0-500 psi		1/4" npt	
PMP119	Delivery Pump	D.I. Water	350 psi	ambient	5-75 ml/min (.08-1.2 gal/hr)			1/2" npt	
PR171	Pressure Regulator	Compressed Air	1250psi inlet	ambient		0-500psig			
PRV139	Pressure Relief Valve	Reactor Vent	400 psi	500F		500psi Vent Pressure		3/4" x 1"	high as possible
PRV139	Pressure Relief Valve	Reactor Vent	400 psi	500F		500psi Vent Pressure		3/4" x 1"	high as possible
ST173	Steam Trap	Steam	350 psi	500F				1/2" npt	
BV125	Solenoid Valve	Analyzers	150 psi	ambient					0.2-1
TC127	Thermocouple								
TC111	Thermocouple								
TC137	Thermocouple								
*SG123	Steam Generator	D.I. Water	350 psi						
*CYC149	Cyclone	Product Filter	350psi						
PG101	Pressure Gauge / Transducer	Air	100psi						
PG181	Pressure Gauge / Transducer	Steam	350 psi						
PG179	Pressure Gauge / Transducer	Steam	350 psi						
FI 185	Flow Indicator	Water	350 psi						
MV 187	Metering valve	Water	350 psi						
BV 189	Ball Valve	Water	350 psi						
BV 135	Actuated Ball Valve	Steam	350 psi						
BV191	Ball Valve	Product Gas	350 psi						
BV193	Ball Valve	N2 (Coal Feed)							
*In-House Items									

Air/N2 feed system

An air pressure booster (AB107) is used to increase the pressure of shop air from 80 psi to 300 psi. The three-way valve (BV167) feeds either this high-pressure air or high-pressure nitrogen to the reactor when ball valve 113 (BV113) is open. A transmitting flow indicator (FIT109) measures and displays the flow rate of the gas.

Coal delivery system
The coal delivery system will include a tube filled with coal flanked by two actuated ball valves (BV143 and BV145). A charge of high-pressure N_2 will be accumulated behind BV143, then both actuated ball valves will be opened simultaneously, allowing the N_2 to force the coal into the reactor. This system will be tested and optimized independently prior to its use in the bench-scale system.

Product gas conditioning and analysis
As the product gas exits the reactor it will pass through a cyclone for particulate removal (CYC149), followed by a condenser for water removal (CND151). The backpressure regulator (BPR153b) will ensure that the reactor maintains its operating pressure. After measurement of the dry flow rate (FI155), a portion of the gas will flow to the analyzer rack for concentration measurements.

Control system
The control system consists of a series of manual switches for the actuated valves. One switch will be used to control the feed to the reactor. When air or N_2 is flowing to the reactor, BV113 is open, requiring BV129 to be closed. These two valves cannot be open at the same time. When BV129 is closed, BV135 must be open, allowing excess steam pressure to be vented via the backpressure regulator (BPR153a). Conversely, when steam is flowing to the reactor, BV129 is open and BV135 and BV113 are both closed. These relationships have been hard-wired into the control system. In the event of an emergency shutdown, all valves will be closed except BV159 and BV135, which will prevent any build-up of pressure in the system.

Data acquisition system
The data acquisition system is comprised of a computer with Labview™ software and Field Point™ hardware. Thermocouples, pressure transmitters, differential pressure transducers, and flowmeters are wired to Field Point™ modules that communicate with the Labview™ software to acquire and record signals, converting them to temperatures, pressures, differential pressures, and flowrates, respectively. In addition, measurements of concentration by the gas analyzers will be recorded by the data acquisition system.

Reactor Design

Significant work has been conducted on the reactor design. A stress analysis was conducted on the final design and safety factors identified. Due to the high operating pressures and temperatures (300psi and 1000 C, respectively), a stress analysis was critical to identifying the operating limits and the safety factors associated with the design. A heat transfer analysis was also conducted to ensure that the gasket temperature at the top of the reactor did not exceed gasket material constraints. The updated design selected for construction is illustrated in Figure 4. The reactor enclosure, or outer shell, and the inner shell that houses the fluidized bed are shown with their dimensions in Figure 4a. The assembled unit is depicted in Figure 4b. A detailed description of the methodology used for the stress analysis, safety factors, and heat transfer is provided in Appendix B.

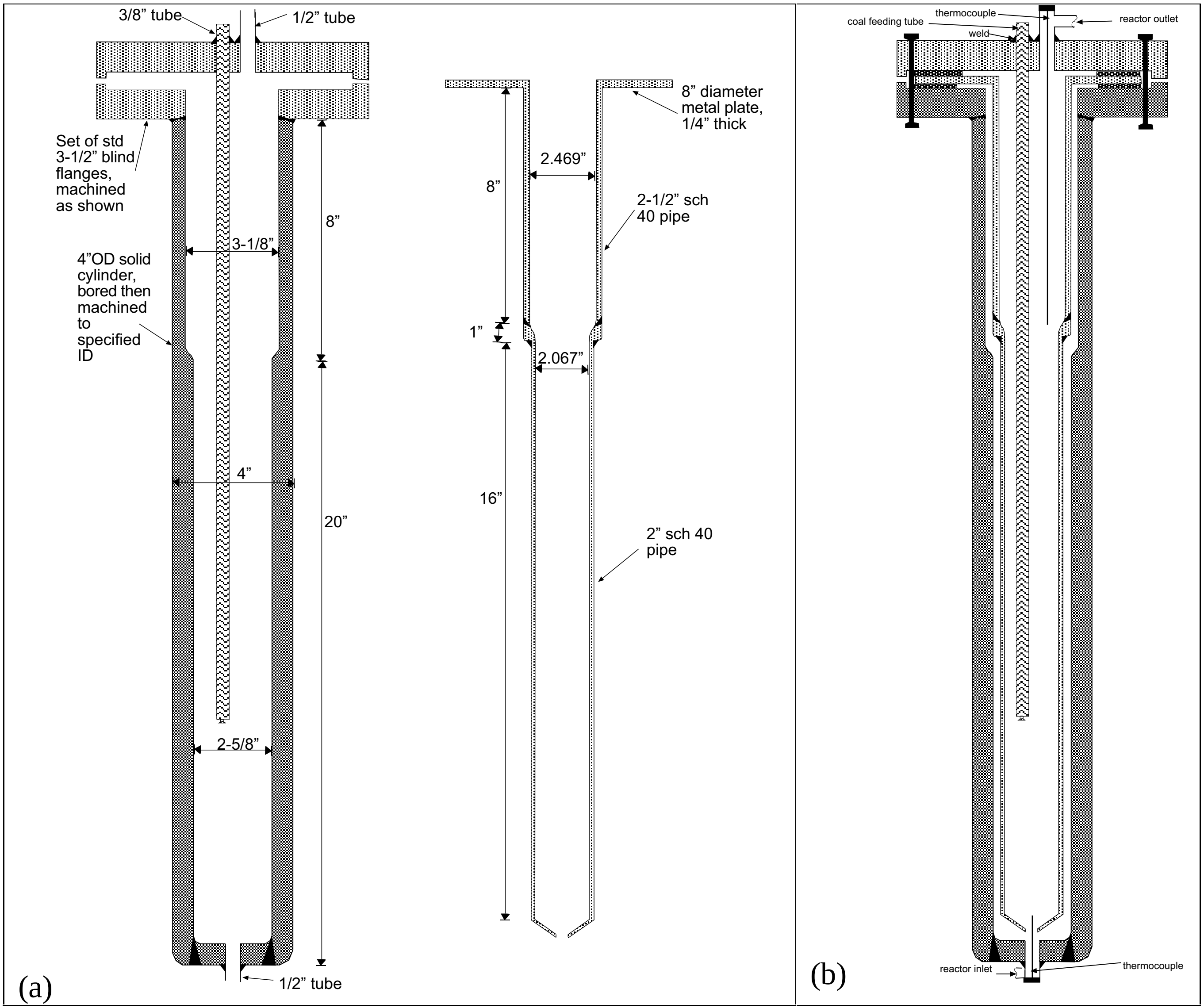


Figure 4. Reactor enclosure and insert assembly. The two separate pieces are shown in (a), while (b) shows how the insert fits inside the enclosure.

ENGINEERING & MODELING STUDIES (Task 4)

Significant progress has been made on the Opportunity Fuels Resource Assessment (Subtask 4.1). The objective of this subtask is to identify and select alternative "opportunity" fuels to be tested in conjunction with coal in experimental evaluations of the AGC process. Work conducted to date includes development of an extensive bibliography as well as a compilation of information based on literature searches, previous opportunity fuel assessments and discussions with experts in the opportunity fuel industry (including fuel producers, fuel handlers, fuel users, fuel recyclers, etc.).

A summary of quantitative information is provided in Appendix C. This includes estimates of the total amount of each fuel type that is generated per year, the amount of fuel that is available, its cost, and the location of its source. For some fuel categories, additional estimates are provided of the amounts used as fuel, recycled, landfilled, or not recoverable.

Additional information gathered for different fuel categories includes:

- A description of the fuel type and source,
- Procedures used for estimating total fuel production rates,
- Estimated availability, and
- Cost.

This information is provided in Appendix C.

SUMMARY AND CONCLUSIONS

Progress has been made in Tasks 1, 2, and 4 in this quarter. The Task 1 lab-scale effort has made significant progress in constructing and testing the furnace for high-temperature testing. In addition, cold-flow modeling and plug-flow reactor testing have provided insight into some of the fundamental fluidization, kinetic and thermodynamic relationships that will have an impact on AGC system operation.

The bench-scale (Task 2) system is near completion, with shakedown testing already in progress on select subsystems. Figure 5 shows the bench-scale system control room. The tall gray gas analyzer and data acquisition rack is shown, as are the two large blue furnace controllers (one for the steam preheater and one for the main furnace). The data acquisition system/computer is also shown.

Figure 5. Bench-scale system control room.

Figure 6 is a photograph of the bench-scale test stand, with the control room in the background (behind the closed door). The main furnace is located on a raised platform, while the air and nitrogen feed lines are arranged along the back of the platform. The steam preheater furnace is located underneath the platform to minimize the length of the preheated steam line, which will enter the bottom of the main furnace. The majority of the piping has been completed, and the wiring of the furnaces, control system, data acquisition, and safety systems are nearing completion. The entire system is located under a large sloped roof to provide protection from the elements.

Figure 6. Bench-scale test stand.

The opportunity fuels resource assessment (Subtask 4.1) is in progress, identifying the types, amounts, costs and locations of opportunity fuels in the United States.

FUTURE WORK

Activities for the fourth quarter will focus on the completion of the bench-scale system construction and shakedown testing (Task 2) as well as on initiation of experimental bench-scale testing (Task 3) as well as continuing work in lab-scale experiments (Task 1) and engineering and modeling studies (Task 4).

Task 1 Lab-Scale Experiments – Fundamentals
Task 1 activities will include the continued development and testing of the lab-scale high-temperature, high-pressure reactor and furnace, along with its auxiliary systems for steam and coal delivery. Additional testing will be conducted using cold-flow modeling and plug-flow furnace test systems in order to further identify the important fluidization and kinetic parameters related to the AGC process, aiding in design and testing of the bench and pilot-scale test units.

Task 2 Bench-scale test facility
The assembly and shakedown testing of several of the bench-scale auxiliary systems has been completed. Future work will focus on the final assembly and shakedown testing of the steam preheating system, the reactor, and the product gas measurement and condenser systems. The data acquisition system will also be finalized and tested. Safety and environmental procedures and controls will be documented and implemented.

Task 3 Bench-scale testing
Testing of the bench-scale system will be initiated in the fourth quarter and will focus on reactor design testing as well as conducting high-temperature, high-pressure tests using model-based operating conditions. The baseline performance of the system will be assessed using measurements of the hydrogen production rate, CO_2 isolation efficiency, and hot gas temperatures. A testing plan and analysis methodology will be developed and implemented. Coal and mineral samples will be selected for experimental testing.

Task 4 Engineering & Modeling Studies
A summary reports will be prepared for both the opportunity fuels resource assessment and the preliminary economic assessment will be conducted. Kinetic and process modeling will continue in the fourth quarter, with the models being used to identify initial operating conditions for lab-scale and bench-scale testing efforts. As experimental testing results are generated, this data will be used to validate the kinetic and process models for their eventual use in the design of the pilot plant.

APPENDIX A: COLD-FLOW FLUIDIZATION STUDY

Confidential

Appendix A is provided to U.S. DOE NETL in hard copy only for internal review by DOE project management

APPENDIX B: BENCH-SCALE REACTOR DESIGN

Operating conditions

Initially, any design process incurs various degrees of freedom. Setting boundaries, or operating conditions, will reduce the number of degrees of freedom, thus making the design task practical. In our case, the following conditions must be satisfied:

- The reactor and its outer shell will be fabricated out of Incoloy 800HT (Special Metals Corporation 2001) as utilized elsewhere (Megaritis et. al., 1998).
- The maximum operating pressure will be 300 psi.
- The maximum operating temperature will be 1900ºF.
- The maximum outside diameter of the reactor outer shell will be limited to 4" because of the internal diameter of the furnace already available.

Stress Analysis

Stress analysis was performed with the "Thick-walled Cylinder Theory" applied to cylindrical pressure vessels, which carry fluids at high pressures. These vessels develop both radial and tangential stresses with values dependent upon the radius of the element under consideration. In determining the radial stress, σ_r, and the tangential stress, σ_t, we make use of the assumption that the longitudinal elongation is constant around the circumference of the cylinder, i.e., a right section of the cylinder remains plane after stressing. Figure B-1 illustrates the stress distribution in a pressure cylinder.

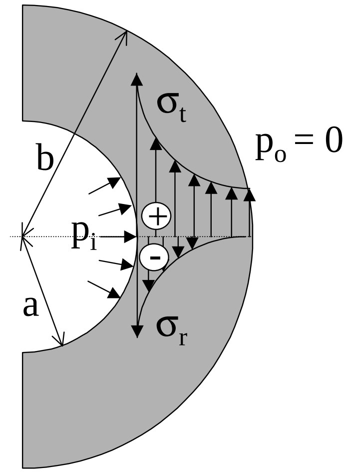


Figure B-1. Distribution of stresses in a thick-walled cylinder subject to internal pressure, p_i, and external pressure, p_o, equal to zero. (A positive stress represents tension and a negative stress represents compression.)

It should be realized that longitudinal stresses, σ_l, exist when the end reactions to pressures are taken by the vessel itself. Derivations of equations to determine these stresses can be found in a textbook by Shigley & Mitchell (1983). Here, we will present only the equations that calculate the maximum stress values, which occur at the inner surface, where r = a:

$$\sigma_t = p_i \cdot \left(\frac{b^2 + a^2}{b^2 - a^2} \right)$$

$$\sigma_r = -p_i \qquad (1)$$

$$\sigma_l = p_i \cdot \left(\frac{a^2}{b^2 - a^2} \right)$$

When the ratio of the wall thickness of a cylindrical pressure vessel to its internal radius (t/a) is about one-twentieth or less, the radial stress that results from pressurizing the vessel is negligible compared to the tangential stress. Under these conditions, it is assumed that σ_t (or hoop stress) and σ_l are uniformly distributed across the wall thickness. This is the "Thin-walled Pressure Vessel Theory", which can be applied to tanks, pipes and tubes:

$$\sigma_t = \frac{p_i \cdot a}{t}$$

$$(2)$$

$$\sigma_l = \frac{p_i \cdot a}{2 \cdot t}$$

This analysis intends to determine the safety factor of an Incoloy 800HT cylindrical vessel as a function of its wall thickness at different temperatures and pressures, and time of operation. Here, the safety factor is defined as the ratio between the maximum allowable stress for Incoloy 800HT, at a particular temperature and time under continuous operation, and the total stress resultant calculated, σ_{total}. The maximum allowable stress, σ_{max}, is taken from the ASME code standards.

Definition of Safety Factor:

$$SF = \left(\frac{\sigma_{max}}{\sigma_{total}} \right), \qquad \text{where:} \qquad \sigma_{total} = \sqrt{(\sigma_t + \sigma_r)^2 + \sigma_l^2}$$

Figure B-2 shows data plotted from ASME tables. Figure B-3 presents calculated safety factors as a function of wall thickness for a cylindrical Incoloy 800HT vessel at 200, 300 or 400 psi of internal pressure and exposed to 1200 or 1900ºF and, after 1,000 h under continuous operation. Calculations were performed using "Thick-walled Pressure Vessel Theory" equations as described above.

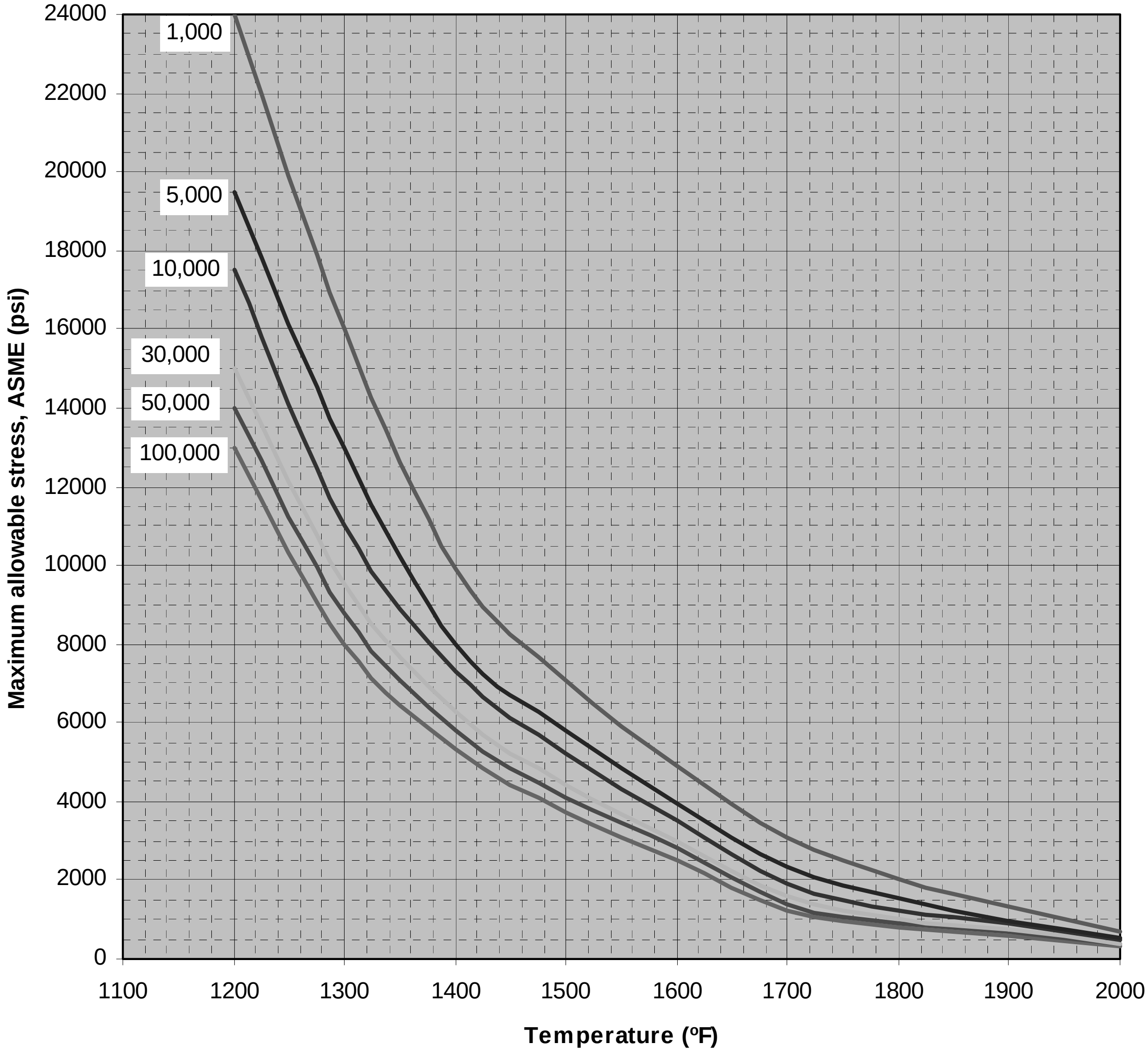
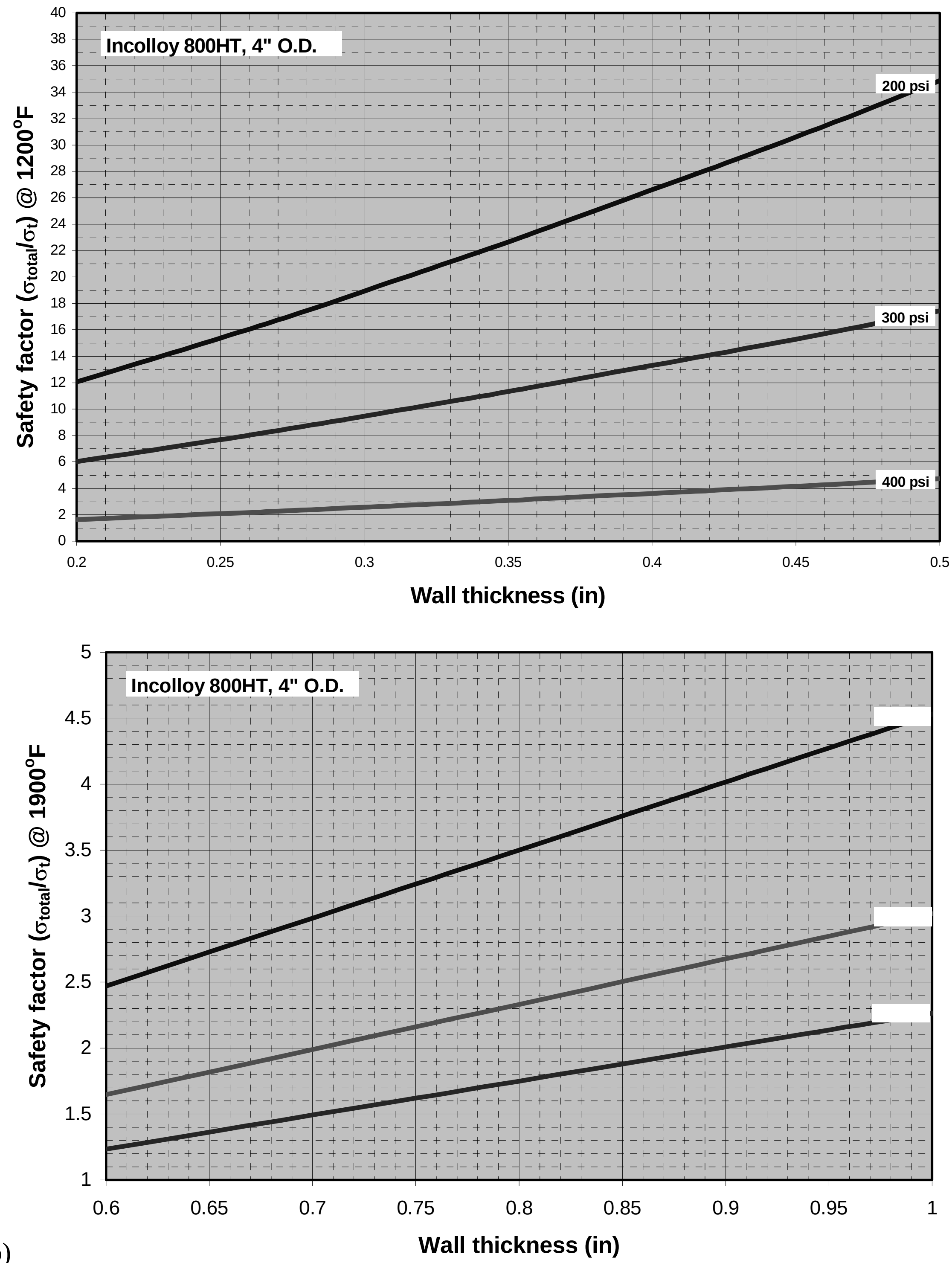


Figure B-2. Data plotted from ASME code standards for Incoloy 800HT for several time periods in hours under continuous operation.



(a)

(b)

Figure B-3. Safety factor at (a) 1200ºF and (b) 1900ºF as a function of wall thickness and different operating pressures (200, 300 and 400 psi), after 1,000 h under continuous operation.

Reactor Specifications

As shown in Figure B-4, the reactor assembly is composed of an outer shell and an inner sleeve (or insert) with internal diameters and wall thickness specified by the stress analysis. The length was specified by estimating heat loss through the reactor outer shell walls to the exterior environment. The heat loss analysis is discussed below.

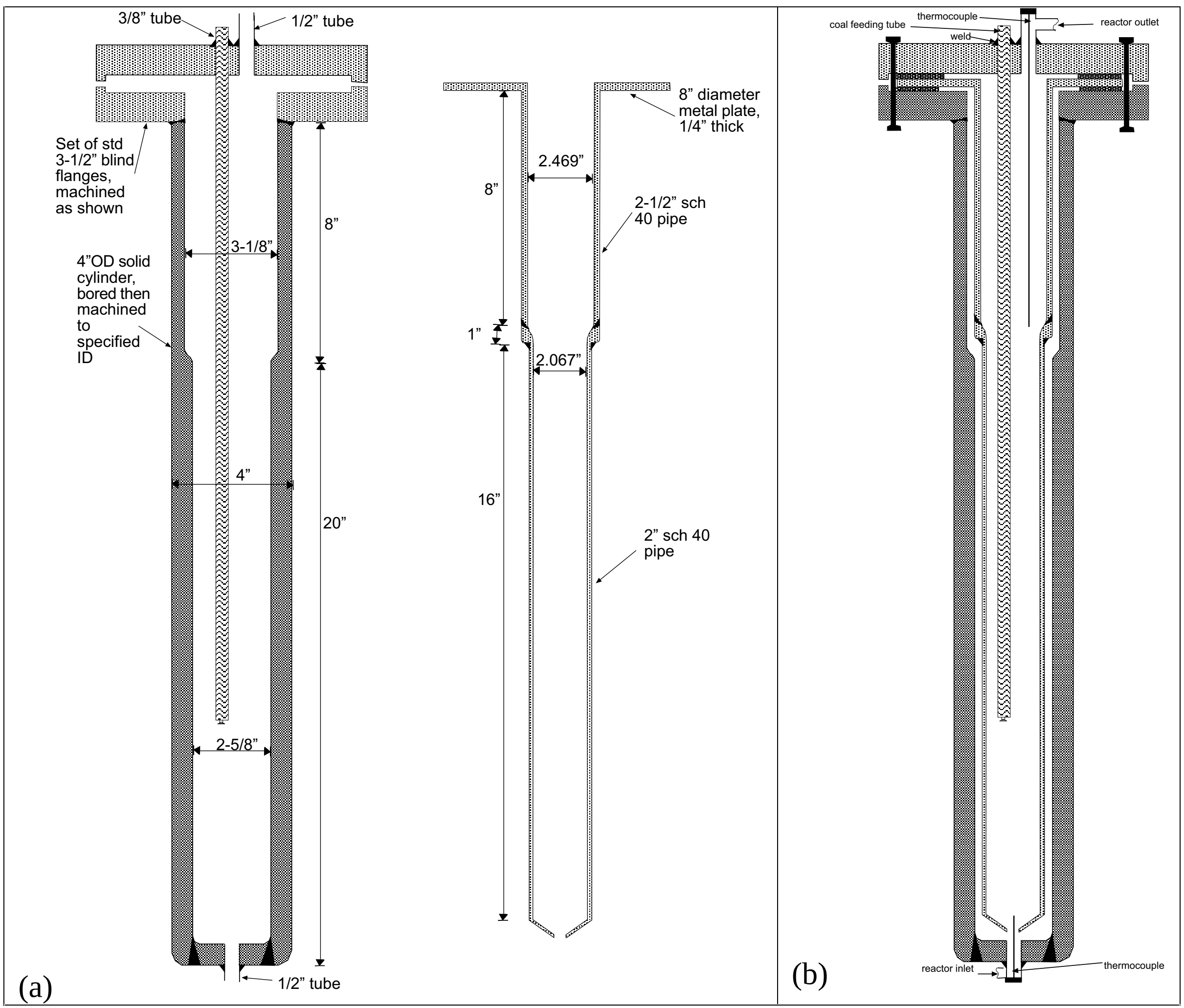


Figure B-4. Reactor outer shell and insert assembly. The two separate pieces are shown in (a), while (b) shows how the insert fits inside the outer shell.

The large pressure differential occurs between the internal and external walls of the reactor outer shell (nearly 300 psi maximum). The inner sleeve will have a negligible pressure difference from inside to outside so we will not consider it for the purpose of stress analysis. About 18" of the reactor (from the bottom up) will be inserted in a high temperature furnace to maintain an average temperature of near 1900ºF within and across the reactor. The remaining 10" of reactor outer shell will be outside the high-temperature furnace exchanging heat to the environment. We estimate this top part of the outer shell will measure an average temperature of ~1200ºF. That means the dimensions of the hot and cold portions of the outer shell must be specified within an acceptable safety factor, as previously defined, to prevent ruptures and, more importantly, personnel injuries. Here, we considered a minimum safety factor of ~2 to be acceptable.

According to Figure B-4a, for the hotter bottom portion of the outer shell (~18") with the dimensions given in Figure B-4a, the safety factor is approx. 1.95 at 300 psi, 1900ºF, and 1,000 h of continuous operation. For the colder top portion (~10") with dimensions given in Figure B-4a, the safety factor is approximately 15 according to Figure B-4a at 300 psi, 1900ºF, and 1,000 h of continuous operation. These operating conditions are extreme and may not be reached in practice, particularly the 1,000 h of uninterrupted operation. Regardless, we consider those safety factors acceptable to ensure proper operation of this equipment. Sensitivity analysis was not conducted here. However, it is clear that the safety factor will improve, in some cases dramatically, as the operating pressure is reduced, or the temperature of exposure of materials is decreased.

Thermal Analysis

Depending on the type of operation, we may have in the outlet of the reactor mostly steam or nitrogen. In any case, the temperature at the reactor outlet will be nearing 1900ºF (~1000ºC).

The goal of this analysis is to estimate the length of un-insulated Incoloy 800HT pipe required out of the high-temperature furnace to allow enough heat loss, thus decreasing the temperature near the top flange to about 750ºF, so the integrity of the gasket utilized would not be compromised (see assembly drawing in Figure B-4b).

Here, we did not run a detailed thermal analysis, which would include accurate temperature profile distributions along and across the wall of the reactor outer shell as well as convective and radiation terms in the fluid stream. Rather, we assumed the temperature profiles in the radial direction in the fluid stream are approximately constant. This does not seem to be a bad assumption if one considers the very low mass flow rates of steam for practical purposes. Steam is the major component of the fluid mixture at a maximum mass flow rate of 13.22 lb/h. Our calculation will consider 2 times this value to allow flexibility in the process operation. The thickness of the insert's thin wall is neglected, so the outer shell is considered the reactor itself with steam at 1900ºF and 300 psi flowing through. Conduction across the outer shell wall and convection/radiation to the external environment were considered in this calculation. The exterior is ambient air at approx. 77ºF.

Figure B-5 shows an illustration of the portion of the reactor outer shell located out of the high-temperature furnace. The 1000ºC region marks the top end of the furnace. The 800ºC mark is a design temperature at the transition region between the narrower and wider diameter. This is the transition to the expansion zone, which is commonly required in fluidization processes to reduce the linear velocity of the gaseous products. A common criterion is to reduce the linear velocity by approximately 2-fold. By applying the equation of continuity at the transition point and assuming the density of the fluid is approximately constant before and after the transition, the results indicate that the ratio of diameters before and after the transition should be on the order of $\sqrt{2}$. (The actual design values utilizing standard tube sizes in Figure B-4a yield a ratio of diameters of about 1.2). At the end of the wider section, near the top flange, we desire a temperature of approximately 400ºC, as explained above.

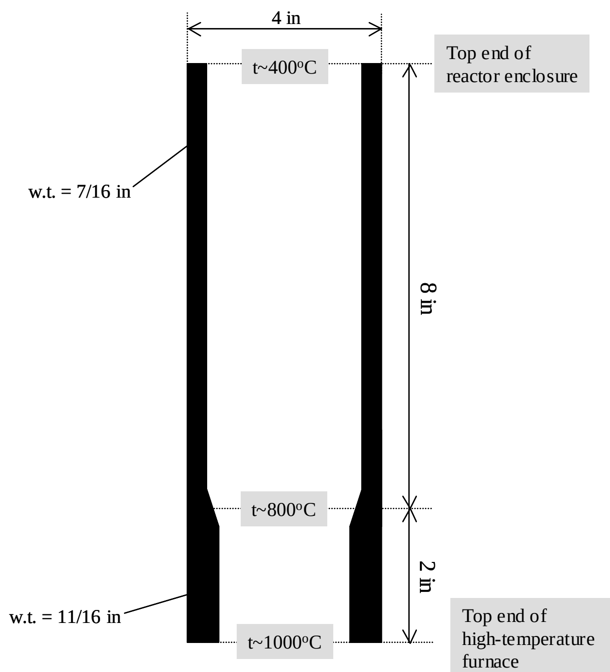


Figure B-5. Portion of reactor outer shell located out of the furnace.

To simplify, we treated this problem in two separate cases. One is an Incoloy 800HT pipe, where steam flow upwards with initial temperature of 1000ºC, exiting at 800ºC. The second case, is an Incoloy 800HT pipe, where steam flow upwards with initial temperature of 800ºC, exiting at 400ºC. Diameters and wall thickness were determined by stress analysis as outlined above.

The spreadsheets next show the heat transfer calculations involved in the estimate of the length given in Figure B-5 above. The length of the narrower piece is estimated in ~2" in order to release heat sufficient to decrease the assembly temperature from ~1000ºC to ~800ºC. As we mentioned before, the length of outer shell/insert inside the high-temperature furnace is ~18". Therefore the total length narrower piece is ~20" as shown in Figure B-4a. As for the wider piece, it is required ~8" to decrease the temperature from ~800ºC to ~400ºC near the flange/gasket assembly.

Below is a spreadsheet showing the estimated pipe length of the part of the reactor outer shell (with narrower internal diameter), which is out of the high-temperature furnace:

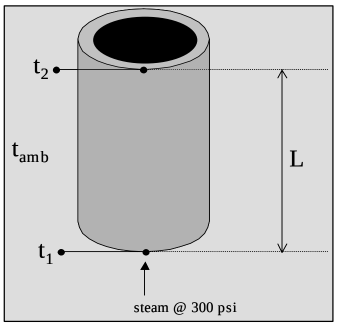
Dimensions of the reactor enclosure out of reaction zone (furnace):

External diameter of tube: D =	4	in
Expansion zone (ratio of internal diameters): D_2/D_1 =	1.414214	
Wall thickness in narrower zone: x_1 =	0.6875	in
Internal diameter in narrower section: D_1 =	2.625	in
Internal diameter in larger section: D_2 =	3.712311	in
Wall thickness in narrower zone: x_2 =	0.143845	in

Other design conditions:

Mass flow of steam:	m_f =	26.44	lb/h
Temperature at the end of reaction zone: t_1 =		1000	°C
		1832	°F
External ambient temperature:	t_{amb} =	25	°C
		77	°F
Internal system pressure:	P =	300	psi
Specific heat of steam @ t_1:	c_p =	0.592	BTU/lb.°F

End temperature t_2		Δt_{ln} (°F)	c_p (BTU/lb.°F)		Q (BTU/h)	k_s	$(h_c + h_r)$	Conductive	Convection +	Pipe length
°C	°F		@ t_2	average		(BTU/h.ft.°F)	(BTU/h.ft^2.°F)	term	Radiation	(in)
400	752	1130.284735	0.495	0.541332	10043.52	12.25748062	12.65525874	0.0057273	0.079018535	8.6291684
600	1112	1363.462238	0.526	0.558025	6912.892	13.47000364	16.79706991	0.00521175	0.059534193	3.76167981
800	1472	1568.118809	0.559	0.575263	4013.624	14.53421781	20.96991226	0.00483014	0.047687372	1.54033227



Also below is a spreadsheet showing the estimated pipe length of the part of the reactor outer shell (with wider internal diameter), which is out of the high-temperature furnace:

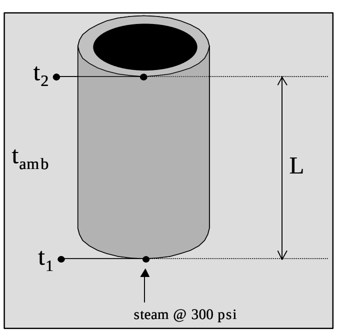
Dimensions of the reactor enclosure out of reaction zone (furnace):

External diameter of tube: D =	4	in
Expansion zone (ratio of internal diameters): D_2/D_1 =	1.414214	
Wall thickness in narrower zone: x_1 =	0.6875	in
Internal diameter in narrower section: D_1 =	2.625	in
Internal diameter in larger section: D_2 =	3.712311	in
Wall thickness in narrower zone: x_2 =	0.143845	in

Other design conditions:

Mass flow of steam:	m_f =	26.44	lb/h
Temperature at the end of reaction zone: t_1 =		800	°C
		1472	°F
External ambient temperature:	t_{amb} =	25	°C
		77	°F
Internal system pressure:	P =	300	psi
Specific heat of steam @ t_1:	c_p =	0.592	BTU/lb.°F

End temperature t_2		Δt_{ln} (°F)	c_p (BTU/lb.°F)		Q (BTU/h)	k_s	$(h_c + h_r)$	Conductive	Convection +	Pipe length
°C	°F		@ t_2	average		(BTU/h.ft.°F)	(BTU/h.ft^2.°F)	term	Radiation	(in)
400	752	991.8215997	0.495	0.541332	6872.702	11.53747232	10.50456099	0.00107822	0.095196744	7.64469162
600	1112	1206.05848	0.526	0.558025	3923.75	12.65150409	13.92962608	0.00098328	0.071789436	2.71302735
800	1472	-	0.559	0.575263	-	-	-	-	-	-



Steam Generator Design

The steam generator component comprises the generator of saturated steam and the pre-heating coil prior to the fluidization reactor inlet. Saturated steam at 300 psi and at a maximum flow of 13.22 lb/h will be generated by flowing water through a 3/8” SS316 coiled-tube inserted in an electrically heated furnace. At this pressure, the saturation temperature is ~417ºF. From the steam generator, the saturated steam will be pre-heated to near the temperature of the fluidization process, about 1900ºF, in a 3/8” Incoloy 800HT coiled-tube, which is inserted in the high-temperature furnace before the reactor assembly. Both lengths of the steam generator and pre-heater coils were calculated and the results are shown in the spreadsheet below. It turns out that the steam generator coil must be approx. 7 ft in length assuming the furnace will keep a uniform temperature in the order of 900ºF. The Incoloy 800HT pre-heater coil must be approx. 14 ft in length to pre-heat the saturated steam at 300 psi to near the fluidization temperature, assuming the high-temperature furnace will maintain a uniform temperature near 1900ºF.

Below is a spreadsheet with heat transfer calculations to estimate the length of tube required to produce saturated steam at 300 psi, and to pre-heat it to ~1900ºF:

Tubing size (in):	t wall (in)	I.D. (in)
0.375	0.049	0.277

WATER (300 psi)			AIR (300 psi)	
	h (BTU/lb)		T (°F)	h (BTU/lb)
T (°F)	liquid	vapor		
68	35.7		68	124.45
417.43	394.1	1203.9	1652	538.21
752		1399.8		
1652		1899		
1850		2017.9		

HEAT TRANSFER COEFFICIENT

boiling water, forced convection

h = 100 BTU/(ft^2.°F.h)

steam, forced convection

h = 50 BTU/(ft^2.°F.h)

TO VAPORIZE WATER @ 300 psi:

mass flow:	26.44	lb/h
Q =	30887.21	BTU/h

TO RAISE STEAM TEMP. FROM SATURATION POINT TO 1652°F (900°C) @ 300 psi:

Q =	18378.44	BTU/h

STEAM GENERATOR:

T ext (°F)	T water,in (°F)	T water,out (°F)	ΔT_{ln} (°F)	A_{ht} (ft^2)	L (ft)
850	65	417.43	591.39	0.52	7.20
900	65	417.43	642.76	0.48	6.63
950	65	417.43	693.93	0.45	6.14

SECONDARY HEATER:

T ext (°F)	T water,in (°F)	T water, out (°F)	ΔT_{ln} (°F)	A_{ht} (ft^2)	L (ft)
1850	417.43	1652	623.85	0.99	13.65

References

Megaritis, A., Zhuo, Y., Messenböck, R., Dugwell, D.R., and Kandiyoti, R., “Pyrolysis and Gasification in a Bench-scale High-pressure Fluidized-bed Reactor”, Energy & Fuels, 12, 144-151, 1998.

J.E. Shigley and L.D. Mitchell, *Mechanical Engineering Design*, McGraw-Hill, 4th edition, p. 70, 1983.

Special Metals Corporation, 2001 http://www.incoalloys.com/

APPENDIX C: OPPORTUNITY FUELS RESOURCE ASSESSMENT

A preliminary assessment has been made of the cost and availability of a variety of opportunity fuels. The objective of this effort is to identify and select alternative “opportunity” fuels to be tested in conjunction with coal in experimental evaluations of the AGC process. Work conducted to date includes development of an extensive bibliography as well as a compilation of information based on literature searches, previous opportunity fuel assessments and discussions with experts in the opportunity fuel industry (including fuel producers, fuel handlers, fuel users, fuel recyclers, etc.).

An extensive literature search has been performed. Results of the primary findings are summarized in the bibliography provided in this appendix. On-going discussion with fuel experts continue, including those with the DOE’s Oak Ridge National Laboratory “Bioenergy Feedstock Development Program,” which has various activities that are directly related to the objectives of this subtask.

A summary of quantitative information compiled to date is provided in Table C-1. This includes estimates of the total amount of each fuel type that is generated per year, the amount of fuel that is available, its cost, and the location of its source. For some fuel categories, additional estimates are provided of the amounts used as fuel, recycled, landfilled, or not recoverable.

Additional information gathered for different fuel categories includes:

- a description of the fuel type and source,
- procedures used for estimating total fuel production rates,
- estimated availability, and
- cost.

This information is provided below for selected fuel categories.

Field and Seed Crop Residues

<u>Source</u> -- Residues from field and seed crops are the materials (straw or stalks) that remain after harvesting. The major field and seed crops include corn, wheat, sorghum, rice, cotton, and barley. Smaller crops include sunflower and safflower.

<u>Gross Production</u> -- Total amounts of field and seed crop residues are based on crop production information from the U.S. Department of Agriculture, National Agricultural Statistics Service, Crop Production Statistics. This includes total farmed acreage, and crop fields. Residue production factors for each of the different crops are used to estimate the amount of field and seed crop residue. Corn grown for “silage” purposes is not included in these estimates since silage corn is targeted specifically for livestock consumption.

Table C-1. Summary of Biomass and Opportunity Fuel Availability and Cost

Fuel Category	Total Amount Generated	Distribution of Uses: Fuel	Recycle (1)	Landfill	Not Recov	Estimated Amount Available (2)	Cost	Location
	BDT/yr	BDT/yr	BDT/yr	BDT/yr	BDT/yr	BDT/yr	$/BDT	
Field and Seed Crop Residues							20 - 50	
Corn (grain)	294.0	0	0	0	176.4	117.6		Upper Midwest
Wheat	87.0	0	0	0	52.2	34.8		Upper Plains
Sorgham	17.3	0	0	0	10.4	6.9		TX, KS
Rice	9.0	0	0	0	0.9	8.1		CA, AR, LA
Barley	5.8	0	0	0	3.5	2.3		North Plain
Cotton	16.9	0	0	0	10.1	6.8		TX, GA, MS, CA
Woody Agriculture Residues							0 - 10	
Apples	0.7							North
Peaches	0.2							CA, GA, SC
Orange	0.5							FL, CA
Grapes	1.2							CA
Nut	0.3							CA
Agricultural Processing Residue							0 - > 20	
Nut Shells	0.3							CA
Fruit Pits	0.1							CA, GA, SC
Rice Hulls	2.0							CA, AR, LA
Cotton Gin Trash	1.5							TX, GA, MS, CA
Urban Wood Wastes							0 - > 30	Population
Secondary Mill	12.5	6.0	4.4	2.1		1.1		
Construction & Demolition								
Construction	7.0		1.8	5.16		2.6		
Demolition	21.1				14.8	6.3		
Municipal Solid Waste								
Wood	10.0	2.5	0.5	7.0	3.5	3.5		
Yard	15.1	2.3	6.7	6.2	2.3	3.1		
Urban Tree Residues	30.9		6.5	5.3	12.2	12.2		
Used Pallets	5.5		5.5			0		
Railroad Ties	1.4							
Utility Poles	NA							
Landclearing / Chaparral	NA							
Used Tires	NA							
Waste Paper	80.0	8.0	40	32.0	16.0	16.0	-30 - > 20	Population
Waste Plastic	20.0	4.0	1.0	15.0	7.5	7.5	-30 - > 20	Population
Lumber Mill Residues	90.4		89	0		1	> 20	Logging
Forest Logging Slash	100+					44.9	> 20	East, NWest,
Forest Thinnings								Great Lakes
Livestock Manure								
Dairy Cows	24.0		24.0		6.0	18.0	0 - 10	CA, WI, MN, NY
Beef Cattle	34.0		34.0		27.2	6.8		Midwest
Cows Misc. (3)	50.0		50.0		15.0	35.0		Midwest
Pigs	11.5		11.5		3.5	8.1		IA, NC, MN, NE
Chicken Layers	3.7		3.7		0.2	3.5		OH, IA, PA, CA, IN
Chicken Broilers	9.0		9.0		0.5	8.6		AR, AL, GA, NC, MS
Turkeys	4.4		4.4		1.3	3.1		AR, MN, ND
Sheep	2.6		2.6					
Sewage Sludge (Biosolids)	8.0	1.8	3.6	2.4		6.2	-30 - 0	Population

(1) wood: mulch, animal bed, landcover, particle board, plywood
manure: land application (fertilizer)
(2) not already used at fuel or greater value, recoverable
(3) heifer, steer, bull, calf

BDT=bone-dry ton
NA= not available

Availability -- For most of the field and seed crops, the residues are directly incorporated back into the soil; plowed under or tilled back into the soil. Soil incorporation is important because it aids soil stabilization, reduces soil erosion from wind or water, and helps fertilization by replacing nutrients and organic matter. Small amounts are used for grazing or feeding of livestock. The sustainable amount of residues that can be removed depends on a variety of site-specific considerations, including soil characteristics, topography, crop rotation, tillage practices, etc. It has been estimated that 30-60% of the residues could be recovered. For this evaluation, it is roughly assumed that 50% of the residues are recoverable.

Rice straw is a special case where currently much of the straw is disposed of directly in the field through open burning. Open in-field burning has been preferred because it potentially reduces plant disease (stem rot), eradicates insects and pests, maintains some soil nutrients and quality, and helps crop yield. However, due to air quality concerns, allowance of the open burning of rice straw is being phased out in California, for example, thus producing a need for alternative rice straw handling practices. It is estimated that 60% of the rice straw is available.

The residues are available seasonably after crop harvesting.

Cost -- It is estimated that crop residues can be collected at a cost of 25-50 $/BDT (bone-dry ton), depending on various factors including collection procedure, bale size, fertilizer make-up, farmer incentive, etc.

Woody Agriculture Residues

Source – Woody agriculture residues from fruit and nut orchards include tree prunings and tree removal and clearings. Tree types include almond, apple, avocado, cherry, date, fig, grapefruit, grape, kiwi, lemon, lime, olive, orange, peach, pear, pistachio, plum, prune, and walnut.

Gross Production -- Similar to field and seed crops, total amounts of woody agricultural residues are based on crop production information from the U.S. Department of Agriculture, National Agricultural Statistics Service, Crop Production Statistics. This includes total farmed acreage and crop fields. Residue production factors for each of the different crops are used to estimate the amount of woody agriculture residue. Total residue production amounts are shown for the major crops: apples, peaches, oranges, grapes, and nuts (almonds and walnuts).

Availability -- Clearings / removals are a result of periodic replanting or changing land use decisions. They are usually available in the late summer and are a very inconsistent and unreliable source. Currently they are either burned on-site or sold as fuel.

Prunings are handled in a variety of methods, depending on crop type. For nuts, they are collected and burned in the field, or sold as fuel or firewood. For the fruit crops, they are usually incorporated back into the soil as mulch. Collection is hampered by the “stick-like” nature of the prunings, and due to the increased use of in-field chippers. Thus, only 25% is considered potentially available.

Costs – Costs are generally near that required for collection -- 10-30 $/BDT.

Agricultural Processing Residue

Source -- Residues from agriculture processing include rice hulls, nut shells, fruit pits, cotton gin wastes, and sunflower seeds.

Gross Production -- Similar to field and seed crops, total amounts of agricultural processing residues are based on crop production information from the U.S. Department of Agriculture, National Agricultural Statistics Service, Crop Production Statistics. This includes total farmed acreage and crop fields. Residue production factors for each of the different crops are used to estimate the total amount of agricultural processing residue.

Availability -- Nut shells are used as fuel or for animal bedding. Fruit pits are used primarily as fuel. Rice hulls are used as fuel and as livestock bedding. Cotton gin trash is used as fertilizer or landfilled. Shells and pits are available seasonally from April to November. Rice hulls and cotton gin trash are available all year long.

Cost – There are no associated collection costs. Costs are generally low – from 0-15 $/BDT, similar to low-end fuels. Although, in some areas, rice hull prices may be high due to their value as poultry bedding.

Urban Wood Wastes

Source -- Urban wood wastes include the following types: wood and yard trimming wastes that are contained in the "municipal solid waste" stream; construction and demolition debris; urban tree residues; secondary wood mill wastes (furniture, flooring, etc.); used pallets; railroad ties; and utility poles.

Gross Production -- Total generation rates are taken from a variety of recent, diverse studies -- see the Resource Assessment Bibliography.

Availability -- Table C-1 estimates the fate of each of the urban wood waste streams. Uses include: feedstock for fiberboard and particleboard; fuel; salvaging for reuse; landscaping and mulch materials. Availability of co-mingled wood is restricted by the ability to separate it from other waste streams. Separation for reuse is occurring to a limited (though increasing) degree at "material recycling facilities" (MRF). The use of MRFs will increase as landfill tipping fees increase.

Cost -- Urban wood waste costs depend on factors such as: landfill tipping costs (which can range from 20-70 $/ton); value as a feedstock for particle board production and landscaping material, which can be as high as 40-50 $/BDT; degree of wood contamination with other wastes; and the ability to be re-used. Many of the urban wood wastes have low to negative values because they cannot be re-used.

Waste Paper / Plastic

Source -- Waste paper and waste plastic are contained in the municipal solid waste stream.

Gross Production -- Total generation rates are taken from a variety of recent, diverse studies. See the Resource Assessment Bibliography.

Availability -- About 50% of used paper is recovered for re-use. Most of this recycled paper consists of non-contaminated newspapers, magazines, and office and school papers, and has high value as a paper mill feedstock, 50-150 $/BDT.

Very little plastics are currently separated and re-used from the municipal waste stream. Those that are have a high value of > 50 $/BDT.

Like many of the urban wood waste streams, paper and plastics recycling efforts are geared toward separation and recovery of high-value materials. There are only limited efforts to recover low-end mixed paper and plastics.

Costs – Low-value mixed paper and plastic waste costs can range from negative to 15 $/BDT, depending on separation cost and landfill tipping cost.

Lumber Mill Residues

Source -- Lumber mill residues include slag, shavings, trimmings, sawdust, bark, round-off, end cuts, and reject lumber that result from processing operations at sawmills and other lumber plants.

Gross Production -- Mill waste production is taken from numerous previous reports, as shown in the Resource Bibliography.

Availability -- Almost all lumber mill wastes are currently re-used as fuel (in both on-site boilers and off-site power plants) or as feedstock for particleboard-type products, pulp mills, animal bedding, and garden products. Very little is not currently being utilized. Efficient use of lumber mill residues is generally necessary for profitable operations. Production rates are decreasing due to environmental and economic restrictions on logging.

Cost -- Lumber mill residues are unique, as sale prices are significantly higher than collection and processing costs. Costs can range from 10-20 $/BDT.

Forest Thinning / Slash

Source -- Forest slash consists of residues remaining on the forest floor from logging activities. This includes tree branches, tops of trunks, stumps, and leaves. Forest thinnings include trees removed from forests for the purpose of forest health and fire prevention efforts.

Gross Production -- Gross production is taken from that reported by Walsh et al. (1999).

Availability -- Forest slash is not considered high enough quality for use in lumber mills. It is usually collected into a pile at the logging location. The pile is either left in place, burned, or removed for use as fuel, landscaping material, paper production, etc. Future availability may be impacted by environmental and ecological interests.

Similarly, the future availability of forest thinnings is uncertain due to political, environmental, economic, and ecological forces. However, many predict that forest thinning (as well as "chaparral" collection) will be the most important and largest supply of future biomass-based fuel, particularly due to fire prevention efforts and urban / suburban sprawl. Note that forest thinnings include those on slopes of less than 30 degrees. Those on greater slopes are difficult to harvest.

Costs – In-forest residues can cost 25-45 $/BDT to process (collect, chop, chip). Costs depend widely on ground slope, collection procedure, road access, etc. Forest thinning costs are comparable.

Livestock Manure

Source – Manure is generated from a variety of livestock operations including: cows (beef and dairy), chicken (layers and broilers), turkeys, pigs, and sheep.

Gross Production – Manure generation rates are based on livestock production information from the U.S. Department of Agriculture, National Agricultural Statistics Service, Crop Production Statistics. Residue production factors for each of the different livestock types are used to estimate the total amount of livestock manure.

Availability – Livestock manures are collectable from "Concentrated and Confined Animal Feedlot Operations." The recent trend has been to raise animals in this type of arrangement. Alternatively, manure from cattle raised in open pastures is not available (not collectable). Manure from cattle feedlot operations is generally collected dry. Manure from dairy and pig operations can be collected either in a wet slurry or a dry scraped manner. Poultry manure is collected in dry stacks. All manures are currently used as fertilizer -- much used for on-site needs, some given or sold for off-site use. However, alternative uses (or treatment prior to use as fertilizer) are currently being driven strongly by concerns from: (1) surface and groundwater contamination (ammonia, nitrates, pathogens) from manure and manure runoff; (2) air emissions, including methane, VOCs, and ammonia from anaerobic digestion; and (3) odor and fly problems. In particular, EPA and the USDA have very recently promulgated rules that will include the requirement to develop comprehensive manure handling, treatment, and management plans.

Cost – Costs for manure range from 0-10 $/wet ton. Costs may decrease as restrictions grow on its use as fertilizer.

Sewage Sludge (Biosolids)

Source – Sewage sludge (biosolids) is produced as a byproduct of the treatment of raw sewage.

Gross Production – Total sewage sludge production is based on a variety of estimates, including that from Goldstein (2000).

Availability – Raw sewage is most commonly handled and treated at Publicly Owned Treatment Works, run by local municipalities. Sewage sludge is burned (mostly on the east coast), some is sent to landfills and used as landfill cover, and much is treated through digestion and composting, and used as fertilizer. Like livestock manures, there has been recent focus on the use of sewage sludge as a fertilizer.

Cost – Sewage sludge is likely accepted at a tipping fee, which is dependent generally on the local landfill cost.

Bibliography: Biomass Resource Assessment

General Assessments

Walsh, M. E., R.L. Perlack, A. Turhollow, D.T. Ugarte, D.A. Becker, R.L. Graham, S.E. Slinsky, and D.E. Ray, "Biomass Feedstock Availability in the United States: 1999 State Level Analysis," Oak Ridge National Laboratory Bioenergy Feedstock Development Program, April 30, 1999, Updated January, 2000, http://bioenergy.ornl.gov/resourcedata/index.html.

Rooney, T. (NEOS Corporation, Lakewood, CO), "Lignocellulosic Feedstock Resource Assessment," Prepared for National Renewable Energy Laboratory, NREL/TP-580-24189, September 1998.

Wright, R.J., W.D. Kemper, P.D. Millner, J.F. Power and R.F. Korcak, "Agricultural Uses or Municipal, Animal, and Industrial Byproducts," U.S. Department of Agriculture, Agricultural Research Service, Conservation Research Report No. 44, 1998.

Tyson, K. S., "Resource Assessment of Waste Feedstocks for Energy Use in the Western Regional Biomass Energy Area," Energy and Environmental Analysis Division, Solar Energy Research Institute, Golden, CO, Prepared for Western Regional Energy Program, February 1991.

JAYCOR, "Regional Assessment of Non-Forest Related Biomass Resources," Prepared for the Southern Regional Biomass Energy Program, Rpt. No. 684-0035a/90, March 1990.

Field / Seed Crops

U.S. Department of Agriculture, National Agricultural Statistics Service, Crop Production Statistics, 2001.

Hettenhaus, J.R., and R. Wooley, "Biomass Commercialization Prospects in the Next 2 to 5 years. Biomass Colloquies 2000," Prepared for National Renewable Energy Laboratory, Golden, CO, NREL/ACO-9-29-039-01, October 2000.

Glassner, D.A., J.R. Hettenhaus, and T.M. Schechinger, "Corn Stover Collection Project," Presented at BioEnergy '98: Expanding BioEnergy Parterships, 1998.

Bluemle, W.J., E. Gonzalez-Clements, and L.D. Clements, "Farmers Attitudes Towards Utilization of Field Residues: Implications for Energy Conversion Policy," Proceedings of the 1998 Biomass Conference, Madison, WI, 1998.

Urban Wastes

Fehrs, J.E., "Secondary Mill Residues and Urban Wood Waste Quantities in the United States," Prepared for Northeast Regional Biomass Program, Washington, D.C., December 1999.

Bush, R.J., V.S. Reddy, and P.A. Araman, "Construction & Demolition Landfills and Wood Pallets - What's Happening in the U.S.," Pallett Enterprise, pp. 27-31, Richmond, VA, March 1997.

Franklin Associates (Prairie Village, KS), “Characterization of Building-Related Construction and Demolition Debris in the United States,” Prepared for the U.S. Environmental Protection Agency, Municipal and Industrial Solid Waste Division, Office of Solid Waste, Report No. EPA-530-R-98-010, June 1998.

Franklin Associates (Prairie Village, KS), “Characterization of Municipal Solid Waste in the United State 1997 Update,” Prepared for the U.S. Environmental Protection Agency, Municipal and Industrial Solid Waste Division, Office of Solid Waste, Report No. EPA-530-R-98-007, May 1998.

Wiltsee, G. (Appel Consultants, Inc. Valencia, CA), “Urban Wood Waste Resource Assessment,” Prepared for National Renewable Energy Laboratory. Golden, CO, NREL/SR-570-25918, November 1998.

McKeever, D.B., “How Woody Residuals Are Recycled in the United States,” BioCycle Journal of Composting and Recycling, pp. 33-44, December 1999.

McKeever, D.B. (USDA Forest Service, Forest Products Laboratory, Madison, WI), “The Changing Solid Waste Resource in the United States, 1990 to 1998,” BioCycle Journal of Composting and Recycling, November 1999.

Ince, P. J., and D.B. McKeever, “Recovery of Paper and Wood for Recycling: Actual and Potential,” USDA Forest Service, Forest Products Laboratory, Madison, WI, Technical Report FPL-GRR-88, November 1995.

Timber / Forest

USDA Forest Service, “Forest Inventory and Analysis Timber Product Output (TPO) Database Retrieval System Developed in Support of the 1997 Resources Planning Act (RPA) Assessment,” http://srsfia.usfs.msstate.edu/rpa/tpo/rpatpo.html.

Sewage Sludge

Goldstein, N., “The State of Biosolids in America, BioCycle Nationwide Survey,” BioCycle Journal of Composting and Organics Recycling, p. 50, December 2000.

National Resource Council (NRC), “Use of Reclaimated Water and Sludge in Food Crop Production,” Washington, D.C., National Academy Press, 1996.

Livestock Manure

U.S. Department of Agriculture, National Agricultural Statistics Service, Livestock Production Statistics, 2001.

U.S. Environmental Protection Agency, “Environmental Assessment of Proposed Revisions to the National Pollutant Discharge Elimination System Regulation and the Effluent Guidelines for Concentrated Animal Feedlot Operations,” U.S. EPA Office of Water, EPA-821-B-01-001, January 2001.

Lander, C.H., D. Moffitt, K. Alt, “Nutrients Available from Livestock Manure Relative to Crop Growth Requirements,” U.S. Department of Agriculture, Natural Resources Conservation Service, Resource Assessment and Strategic Planning Working Paper 98-1, February 1998.

Antares Group Inc, T.R. Miles Technical Consulting Inc., Foster Wheeler Development Corp., “Economic and Technical Feasibility of Energy Production from Poultry Litter and Nutrient Filter Biomass on the Lower Delmarva Peninsula,” Prepared for Northeast Regional Biomass Program, CONEG Policy Research Center, Inc., Washington, D.C., August 2, 1999.