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

Quarterly Technical Progress Report No. 9

Reporting Period:

October 1, 2002 – December 31, 2002

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January 2003

DOE Award No. DE-FC26-00FT40974

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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 process efficiency and environmental impact performance of fossil fuel utilization. GE Energy and Environmental Research Corporation (GE EER) has developed an innovative fuel-flexible Unmixed Fuel Processor (UFP) technology to produce H_2, power, and sequestration-ready CO_2 from coal and other solid fuels. The UFP module offers the potential for reduced cost, increased process efficiency relative to conventional gasification and combustion systems, and near-zero pollutant emissions including NO_x. GE EER was awarded a Vision 21 program from U.S. DOE NETL to develop the UFP technology. Work on this Phase I 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 UFP 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 process modeling work, has an estimated process efficiency of 68%, based on electrical and H_2 energy outputs relative to the higher heating value of coal, and an estimated equivalent electrical efficiency of 60%. The Phase I 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 UFP technology.

This is the ninth quarterly technical progress report for the Vision 21 UFP program supported by U.S. DOE NETL (Contract No. DE-FC26-00FT40974). This report summarizes program accomplishments for the period starting October 1, 2002 and ending December 31, 2002. The report includes an introduction summarizing the UFP technology, main program tasks, and program objectives; it also provides a summary of program activities and accomplishments covering progress in tasks including lab- and bench-scale experimental testing, pilot-scale design and assembly, and program management.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ACRONYMS

ASU	Air Separation Unit
UFP	Unmixed Fuel Processor
CAM	CO_2 Absorber Material
CEC	California Energy Commission
CTQ	Critical to Quality
DFSS	Design for Six Sigma
GE EER	General Electric Energy and Environmental Research Corporation
GHSV	Gas Hourly Space Velocity
GSV	Gas Space Velocity
IGCC	Integrated Gasification Combined Cycle
NETL	National Energy Technology Laboratory
NTI	New Technology Introduction
OTM	Oxygen Transfer Material
P&ID	Process and Instrumentation Diagram
R1	Reactor 1
R2	Reactor 2
R3	Reactor 3
SIU-C	Southern Illinois University – Carbondale
UFP	Unmixed Fuel Processor
U.S. DOE	United States Department of Energy

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. The technology encompassing this concept will be referred to as the *Unmixed Fuel Processor (UFP)* throughout this report. [In previous reports, the technology concept was referred to as Advanced Gasification-Combustion (AGC)]. When commercialized, the UFP technology may become one of the cornerstone technologies to fulfill Vision 21 energy plant objectives of efficiently and economically producing energy and hydrogen from coal with utilization of opportunity feedstocks.

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

The Phase I Vision 21 UFP program is being 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 UFP project integrates lab-, bench- and pilot-scale studies to demonstrate the UFP technology. Engineering studies and analytical modeling are being performed in conjunction with the experimental program to develop the design tools necessary for scaling up the UFP technology to the demonstration phase. The remainder of this section presents objectives, concept, and main tasks of the UFP program.

Program Objectives

The primary objectives of the UFP program are to:

- Demonstrate and establish the chemistry of the UFP technology, measure kinetic parameters of individual process steps, and identify fundamental processes affecting process economics.
- Design and develop bench- and pilot-scale systems to test the UFP technology under dynamic conditions and estimate the overall system efficiency for the 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 UFP module into Vision 21 plant design and optimize work cycle efficiency.
- Determine extent of technical/economical viability & commercial potential of UFP module.

UFP technology

The conceptual design of the UFP technology is depicted in Figure 1. The UFP technology makes use of three circulating fluidized bed reactors containing CO_2 absorbing material (CAM) and oxygen transfer material (OTM), as shown in Figure 1. Coal and some opportunity fuels (5-10% by heat input) are partially gasified with steam in the first reactor, producing H_2, CO and CO_2. As CO_2 is absorbed by the CO_2 sorbent, CO is also depleted from the gas phase via the water-gas shift reaction. Thus, the first reactor produces a H_2-rich product stream suitable for use in liquefaction, fuel cells, or turbines.

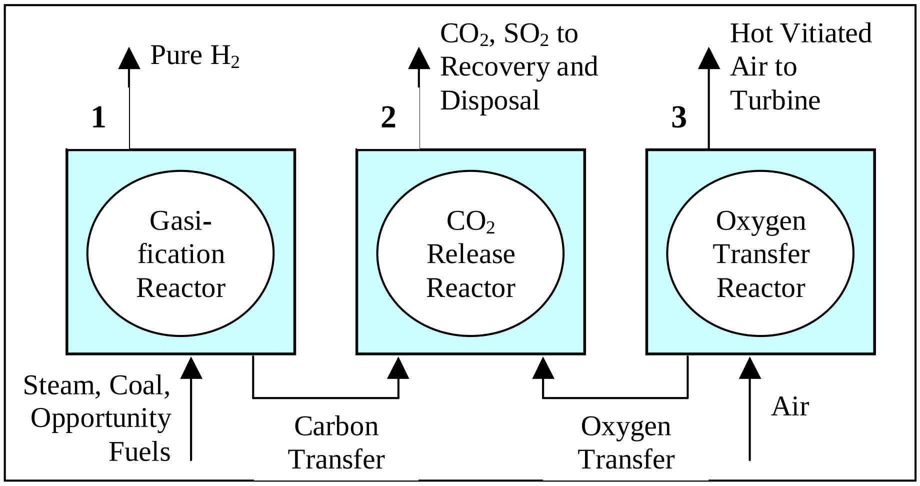


Figure 1. Conceptual design of the UFP technology.

Gasification of the char, transferred from the first reactor, is completed with steam fluidization in the second reactor. The oxygen transfer material is reduced as it provides the oxygen needed to oxidize CO to CO_2 and H_2 to H_2O. The CO_2 sorbent is regenerated as the hot moving material from the third reactor enters the second reactor. This increases the bed temperature forcing the release of CO_2 from the sorbent, generating a CO_2-rich product stream suitable for sequestration.

Air fed to the third reactor re-oxidizes the oxygen transfer material via a highly exothermic reaction that consumes the oxygen in the air fed. Thus, reactor three produces oxygen-depleted air for a gas turbine as well as generating heat that is transferred to the first and second reactors via solids transfer.

Solids transfer occurs between all three reactors, allowing for the regeneration and recirculation of both the CO_2 sorbent and the oxygen transfer material. Periodically, ash and bed materials will be removed from the system and replaced with fresh bed materials to reduce the amount of ash in the reactor and increase the effectiveness of the bed materials.

Project Plan

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

PROGRAM PLANNING AND MANAGEMENT

Program planning activities have focused on meeting the objectives of the program as stated previously. GE EER has made use of several GE methodologies to obtain desired results and systematically conduct program design, construction and testing activities. Methodologies utilized in this program include New Technology Introduction (NTI) and Design For Six Sigma (DFSS). The NTI program is a detailed and systematic methodology used by GE to identify market drivers, and continually ensure that the program will meet both current and future market needs. The NTI program is also strongly coupled with the DFSS and other quality programs, providing structure to the design process and ensuring that the design accomplished through regular program reviews, detailed design reviews, market assessments, planning and decision tools, and specific quality projects aimed at identifying system features and attributes that are critical to quality (CTQ) for customers.

Table 1. Main tasks of the UFP 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

During team meetings, specific aspects of the program were identified for increased scrutiny and rigorousness in design and implementation. These were defined as individual DFSS projects, and cover aspects of the entire program. Figure 2 shows the structure of the DFSS projects completed, planned and in progress, and their relationship to the overall program structure. GE tracks each project by ID number, and each program is reviewed individually by trained six sigma black belts and master black belts.

The project team meets weekly to assess progress, distribute workload, and identify and remove potential roadblocks. An expanded NTI project team that includes senior management and other expert personnel also meets biweekly to gauge progress and ensure that adequate company resources are allocated and technical issues resolved to allow steady progress toward program objectives.

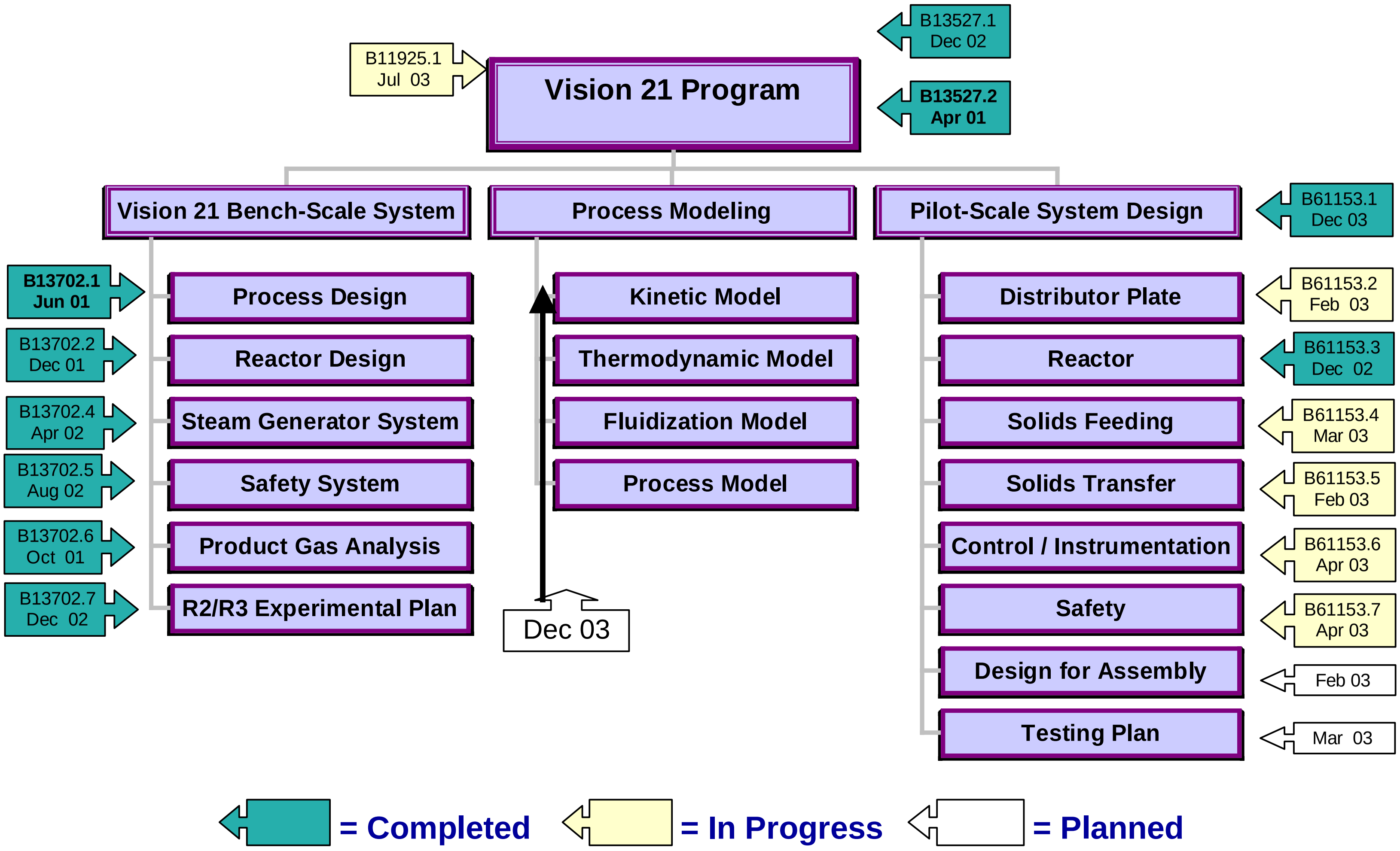


Figure 2. Six sigma projects completed, planned and in progress and their relationship to UFP program structure.

Another purpose of the biweekly NTI meeting is to ensure that the technology is developed in a manner that continues to allow it to meet emerging market needs by following the GE NTI methodology. This includes detailed design reviews as progress is made on system designs and technology performance reviews as results are generated.

Program management activities also involve continuous oversight of program expenditures. This includes monthly review of actual expenditures and monthly projections of labor, equipment, contractor costs, and materials costs.

Technology transfer and networking with experts in the advanced power generation field is an important and ongoing part of project management. Team members continue to seek out opportunities to present the UFP technology and progress at several conferences.

During this reporting period, the GE EER Vision 21 team made preparations for a meeting with several DOE representatives to be held on January 8, 2003 at GE EER's corporate offices in Irvine, CA. During the daylong meeting, the Vision 21 UFP engineering team will provide overviews of the UFP technology, progress to date, and planned technology development activities. The agenda for the meeting is provided as Appendix A. Details of the January 8 meeting with DOE will be provided in the next quarterly report.

An internal NTI Tollgate review of the Vision 21 UFP program was held on December 4, 2002 with senior GE management to establish the feasibility of the system based on bench-scale experimental results. In addition, plans for the demonstration and continued development of the UFP technology were discussed. During the review, the team's efforts at integrating the Design for Six Sigma approach were praised, and the program was approved to receive additional internal funding for 2003 to meet program technical objectives, GE commercialization objectives, and cost-sharing commitment.

During this quarter, additional results from the experimental facilities were obtained, analyzed and used to assess operating characteristics of the system. The laboratory-scale activities are being conducted by SIU in Carbondale, IL, while the bench-scale and pilot-scale systems are located at GE EER's test facility in Irvine, CA.

LABORATORY-SCALE TESTING (Task 1)

The primary objective of Task 1 is to perform a laboratory-scale demonstration of the individual chemical and physical processes involved in GE EER's fuel-flexible UFP technology. Specific objectives of Task 1 include:

- Support bench- and pilot-scale studies;
- Assist in process optimization and engineering analysis;
- Identify key kinetic and thermodynamic limitations of the process; and
- Verify the process parameters at laboratory scale.

Work conducted in the ninth quarter of this program has focused on experiments conducted in a high-temperature fluidized bed reactor.

A designed experimental test matrix was developed to assess the impact of varying temperature and OTM:CAM ratios on hydrogen production and hydrogen purity during the coal gasification step (Reactor 1 conditions). Detailed analysis of the results will be reported after the test matrix experiments have all been completed for both atmospheric and high-pressure conditions. Initial experiments were conducted using the high-temperature fluidized bed reactor at atmospheric pressure. Silica sand (mesh US # 200) representing baseline condition, washed in acid, or mixtures of OTM and CAM were used as the fluidization medium. The experimental conditions are summarized in Table 2.

Fluidization solids were inserted into the reactor, which was heated to the desired temperature under flowing nitrogen at atmospheric pressure. Steam was introduced into the reactor and the nitrogen flow rate was adjusted to provide a total gas flow rate equal to 15 times the minimum fluidization velocity. Coal samples with initial mass of 2.5 g were injected into the reactor using the coal delivery system, driven by nitrogen. Immediately after coal injection, gas samples and mass flow rate data were taken at one-minute intervals for 30 minutes. Gas samples were analyzed using a gas chromatograph.

Table 2. Lab-scale experimental conditions.

Test ID #:	**Temp. [°C]**	**Steam [%]**	**CAM [g]**	**OTM [g]**	**Sand [g]**
1	670	75	0	0	60
2	670	75	40	10	0
3	670	75	40	30	0
4	670	85	40	20	0
5	770	85	40	20	0
6	870	85	40	20	0
7	870	85	30	30	0
8	870	85	50	10	0
9	870	85	0	0	60

A sample output gas flowrate profiles for Test #6 are shown in Figure 3. Test #6 had the highest H_2 output, but also the highest combined total CO and CO_2 output and thus one of the lower H_2 purities. This is likely due to the high gasification temperature (870°C) at which CO_2 absorption by the CAM is minimum, particularly at atmospheric pressure. Such results will be compared to the high-pressure test results once completed. The interactions between these variables may also be explained via a mathematical transfer function relating the variables at the various test conditions.

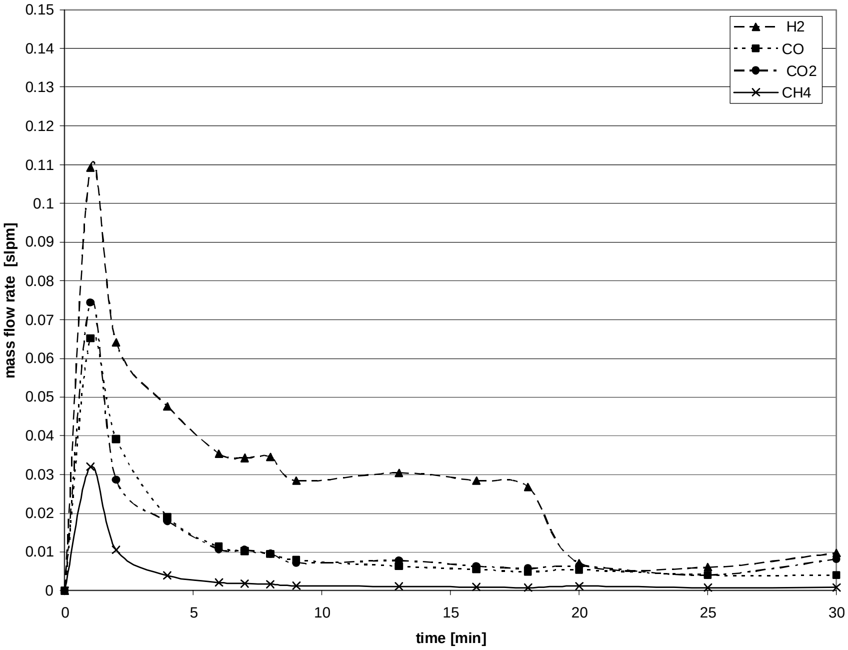


Figure 3. Test #6, product gas mass flow rates, 870°C, 85% steam, 40 g CAM, 20 g OTM.

BENCH-SCALE TESTING (Task 3)

The objectives of the bench-scale testing task are to demonstrate the technical feasibility of the UFP technology and aid in developing modeling tools and pilot plant equipment design. The bench-scale system is also intended to provide data on individual UFP reactor modes to aid in pilot plant design and testing. Bench-scale testing conducted in the ninth quarter has focused on testing and analysis of the OTM reduction/oxidation process.

OTM performance is related to the ability of the OTM to undergo the reduction reactions in Reactor 2 mode that in turn allow the OTM to be oxidized at Reactor 3 conditions. Experiments conducted under Reactor 3 conditions have shown that the oxidation of reduced-state OTM occurs rapidly and readily and is highly exothermic. OTM performance is most often limited by the reduction step. Initial OTM tests were conducted using coal for OTM reduction. Later tests were conducted using CO and H_2 as reducing agents to isolate OTM reduction from coal gasification. The complexity of the behavior observed led to the development of a designed experimental test matrix as described in the second annual report (Oct 1, 2001 – Sep 30, 2002). The experimental test procedure and set-up used for these tests are provided as Appendix B.

The full set of test matrix experiments have been completed. The test conditions and results are presented in Table 3. The test conditions (independent variables) include CO and H_2 concentrations as well as the Gas Hourly Space Velocity (GHSV) or GSV (1/hr), while the % OTM reduction is the main response dependent variable. The first thirteen tests were the full test matrix, while the last two tests were optimization runs completed after analysis of the first thirteen runs. An initial transfer function was developed based on the first thirteen runs, and it was used to identify operating conditions predicted to provide peak OTM reduction. Therefore, the two additional tests were conducted at conditions selected for their high-predicted OTM reduction. The results in Table 3 show that the %OTM reduction achieved in these tests exceeded the performance of all previous test runs and validated predictions of the initial transfer function. An optimized transfer function was then derived based on all fifteen tests based on a surface fit and making use of second-order interactions. This transfer function is provided below:

Table 3. OTM test conditions and results for full test matrix.

Run #	Independent Variables			Response
	Local Feed Conc.		GSV	OTM Reduction
	[CO] vol-%	[H2] vol-%	(hr^-1)	%
1	3.1	12.4	1798	10.6
2	6.4	6.4	1573	9.4
3	0.0	7.1	1718	10.8
4	6.1	12.1	1562	6.9
5	7.4	0.0	1665	10.2
6	0.0	14.7	2144	15.4
7	0.0	13.2	1515	12.8
8	5.5	0.0	3170	11.1
9	3.1	6.2	1931	10.9
10	3.6	0.0	1544	12.9
11	0.0	0.0	2443	4.0
12	6.0	12.0	2527	11.5
13	3.3	6.6	2517	12.7
Opt-1	0.0	13.1	2611	19.0
Opt-2	0.0	14.0	2452	20.0

$$X_{OTM} = 44.7 + 1.6[CO] - 0.93[H_2] - 0.033GHSV - 0.13[CO][H_2] + 8.8\times10^{-4}[H_2]GHSV - 0.17[CO]^2 - 0.013[H_2]^2 + 6.9\times10^{-6}GHSV^2$$

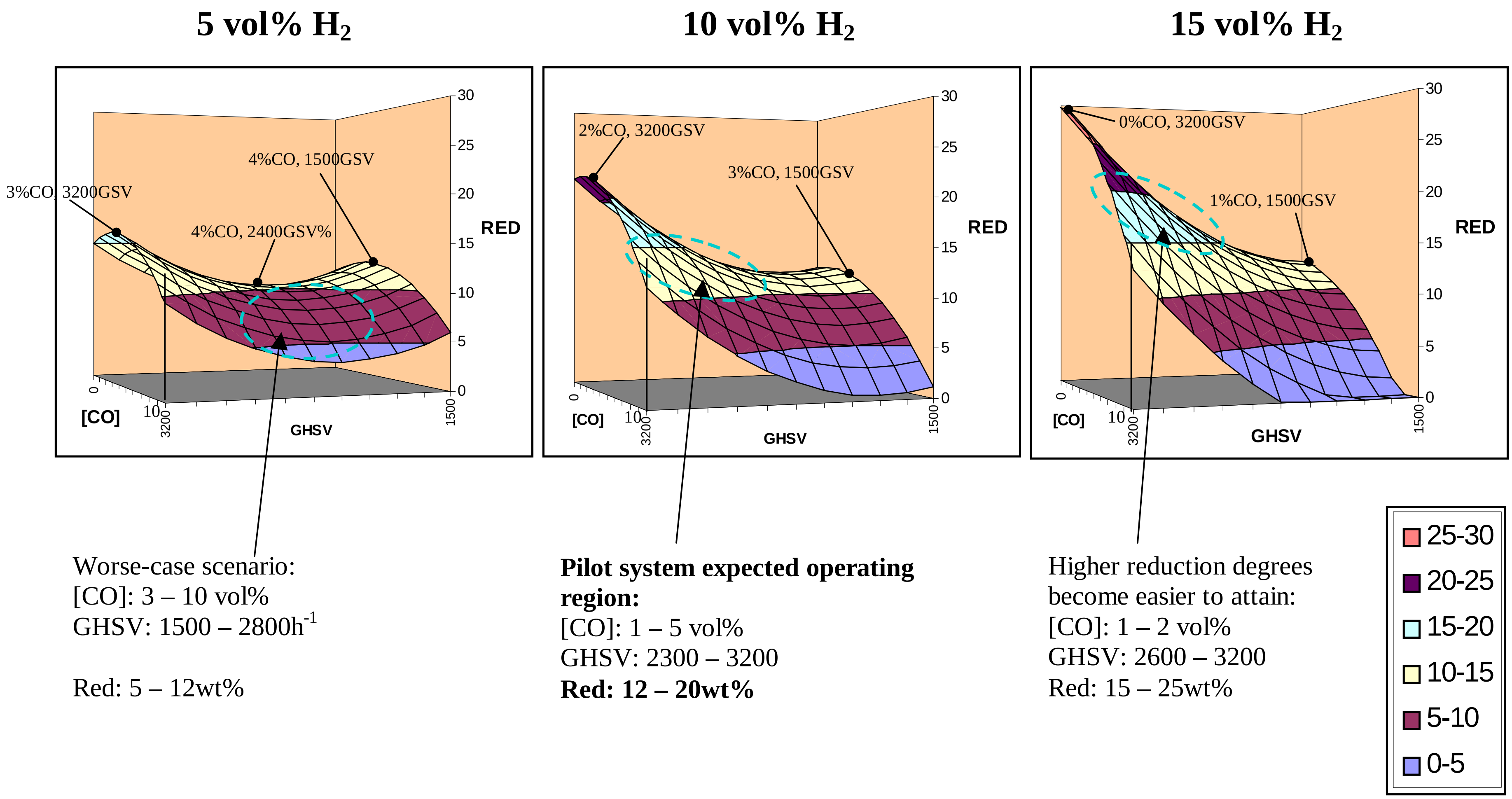
Where:

- X_{OTM} = fraction of OTM reduced (wt%)
- [CO] = concentration of CO at 900°C and 300 psi (0 – 7.4 vol. %)
- [H_2] = concentration of H_2 at 900°C and 300 psi (0 – 14.7 vol. %)
- GHSV = gas hourly space velocity, volumetric steam flow/volume of bed (1500 – 3200)

The 15-test transfer function was used to calculate predicted performance for the actual test conditions, and these predictions were compared to the actual experimental results. The results of this comparison are shown in Table 4, and show excellent agreement. Three-dimensional plots of the effects of CO concentration and GHSV on OTM reduction at three different H_2 concentrations are provided in Figure 4. At 10% H_2 (center plot), the region of expected pilot-scale operation is shown, and is expected to result in reduction of up to 20% of the OTM present in the bed.

Table 4. Comparison of transfer function predictions with actual experimental data.

Predicted Results					
Point	**Actual**	**Pred**	**Resid**	**%Error**	**Rstudent**
1	10.6	11.1	-0.50	4.66	-0.87
2	9.4	9.2	0.16	-1.66	0.25
3	10.8	11.0	-0.20	1.89	-0.39
4	6.9	6.6	0.37	-5.31	0.73
5	10.2	10.3	-0.15	1.50	-0.56
6	15.4	15.8	-0.39	2.52	-0.69
7	12.8	12.8	-0.02	0.12	-0.03
8	11.1	11.2	-0.02	0.15	-0.10
9	10.9	10.7	0.13	-1.20	0.21
10	12.9	12.8	0.06	-0.44	0.37
11	4.0	4.0	0.03	-0.66	0.13
12	11.5	11.7	-0.30	2.60	-0.62
13	12.7	12.5	0.21	-1.66	0.36
14	19.0	19.8	-0.77	4.04	-1.61
15	20.0	18.6	1.39	-6.96	4.20
	Actual	**Pred**	**Resid**	**%Error**	**Rstudent**
Minimum	4.0	4.0	-0.77	-6.96	-1.61
Maximum	20.0	19.8	1.39	4.66	4.20
Average	11.9	11.9	0.00	-0.03	0.09
Std Dev	4.1	4.0	0.48	3.18	1.29



5 vol% H_2

10 vol% H_2

15 vol% H_2

Worse-case scenario:
[CO]: 3 – 10 vol%
GHSV: 1500 – 2800h^{-1}

Red: 5 – 12wt%

Pilot system expected operating region:
[CO]: 1 – 5 vol%
GHSV: 2300 – 3200
Red: 12 – 20wt%

Higher reduction degrees become easier to attain:
[CO]: 1 – 2 vol%
GHSV: 2600 – 3200
Red: 15 – 25wt%

Figure 4. Transfer function predictions of OTM reduction as a function of CO concentration and GHSV for three different H_2 concentrations.

ENGINEERING AND MODELING STUDIES (Task 4)

Process Modeling

The objectives of the process-modeling task are to develop models for the UFP technology, validate them using experimental data, and apply the models to assist in the design and operation of the pilot-scale system. In addition, process models will be used to make meaningful comparisons of the performance of the UFP technology relative to competing technologies.

The process modeling of the UFP technology was performed using Aspen Plus version 11.1. Aspen Plus (Aspen Technology, Inc.) is engineering software that can perform process analysis for various unit operations (including reactions, separations, drying, etc.) and process design calculations for heat exchangers, pumps and turbines. Aspen Plus can also handle steady state processes involving solids such as coal. Some of the solids processing applications that have been modeled with Aspen Plus include:

- The Bayer process
- Cement kilns
- Coal gasification
- Hazardous waste incineration
- Iron ore reduction
- Zinc smelting/roasting

These capabilities make Aspen Plus an ideal process analysis tool for the UFP technology, which includes chemical processes involving solids such as coal, CO_2-absorbing material (CAM), and oxygen transfer material (OTM).

The process flow diagram was constructed in Aspen Plus as shown in Figure 5. The steady state temperatures of several process streams are also included in Figure 5. The major assumptions involved in the process analysis are listed below:

1. The three reactors (gasifier, CO_2 separator and oxidizer) were assumed to be thermodynamically limited at steady state (Gibbs reactors).
2. The maximum temperature of the oxygen transfer material was limited to 1361^oC at steady state.
3. The maximum metal temperature in the heat exchangers was limited to 650^oC.
4. The process was conducted at 30 atm pressure.
5. Advanced gas turbines and pumps were assumed to be available (with isentropic efficiency of 90%).
6. The process analysis was carried out for Illinois #6 Old Ben #26 Mine coal (HHV 11,666 Btu/lb).

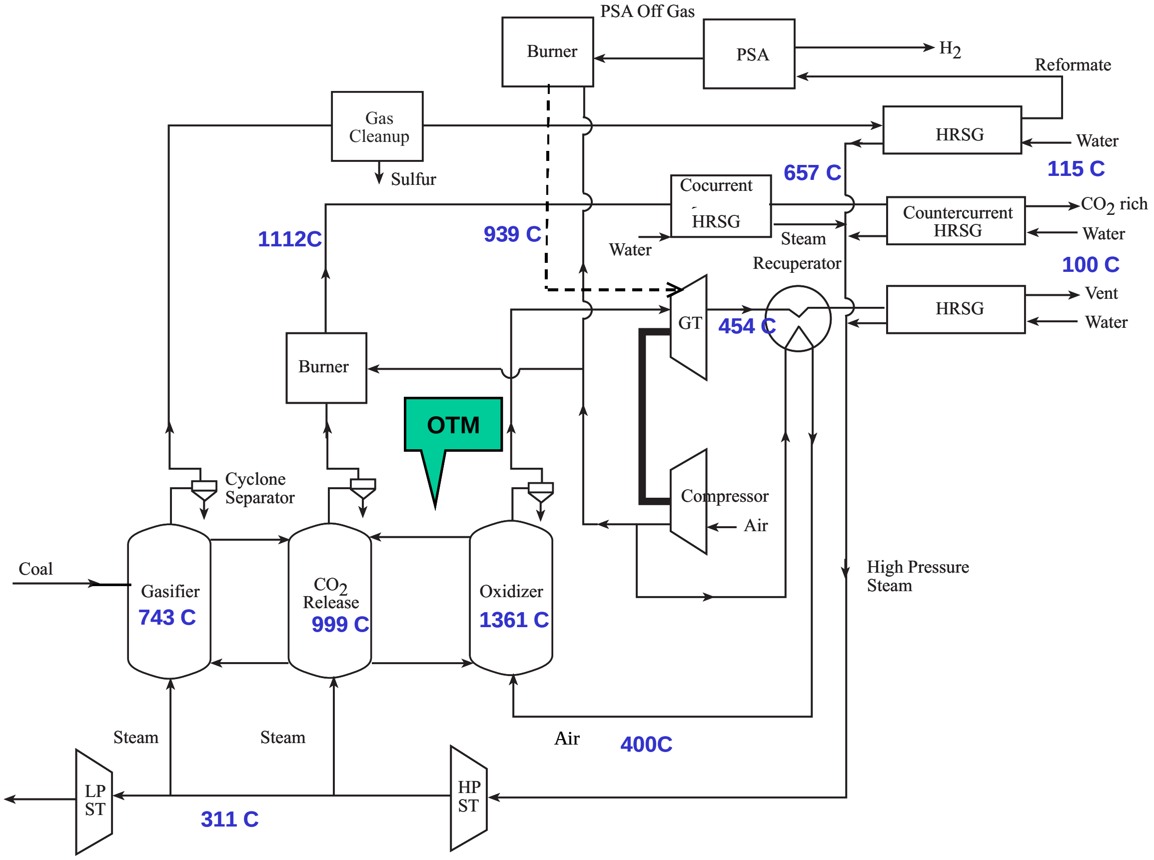


Figure 5. Process flow diagram for UFP technology for co-production of hydrogen and electricity (1:1) from coal.

UFP efficiency estimates and comparison with advanced IGCC process efficiency

The efficiency of the process configuration was estimated as follows based on the results obtained using the Aspen Plus simulations.

$$\textbf{Efficiency, \%} = \frac{\textbf{HHV of } \mathbf{H_2} \textbf{ produced (MW) + Net electricity (MW)}}{\textbf{HHV of Coal fed (MW)}} \textbf{ X 100 \%}$$

The equivalent electrical efficiency was obtained assuming that the H_2 generated in the process is utilized in a solid oxide fuel cell/combined cycle combo with 75% overall efficiency.

$$\textbf{Equivalent electrical efficiency \%} = \frac{\textbf{0.75 *HHV of } \mathbf{H_2} \textbf{ produced (MW) + Net electricity (MW)}}{\textbf{HHV of Coal fed (MW)}} \textbf{ X 100 \%}$$

The process efficiency of the UFP system was compared to an advanced IGCC process. In modeling the advanced IGCC system, the assumptions involved in the process model were kept similar to those of the UFP technology model. The process flow diagram of the modeled IGCC system is shown in Figure 6.

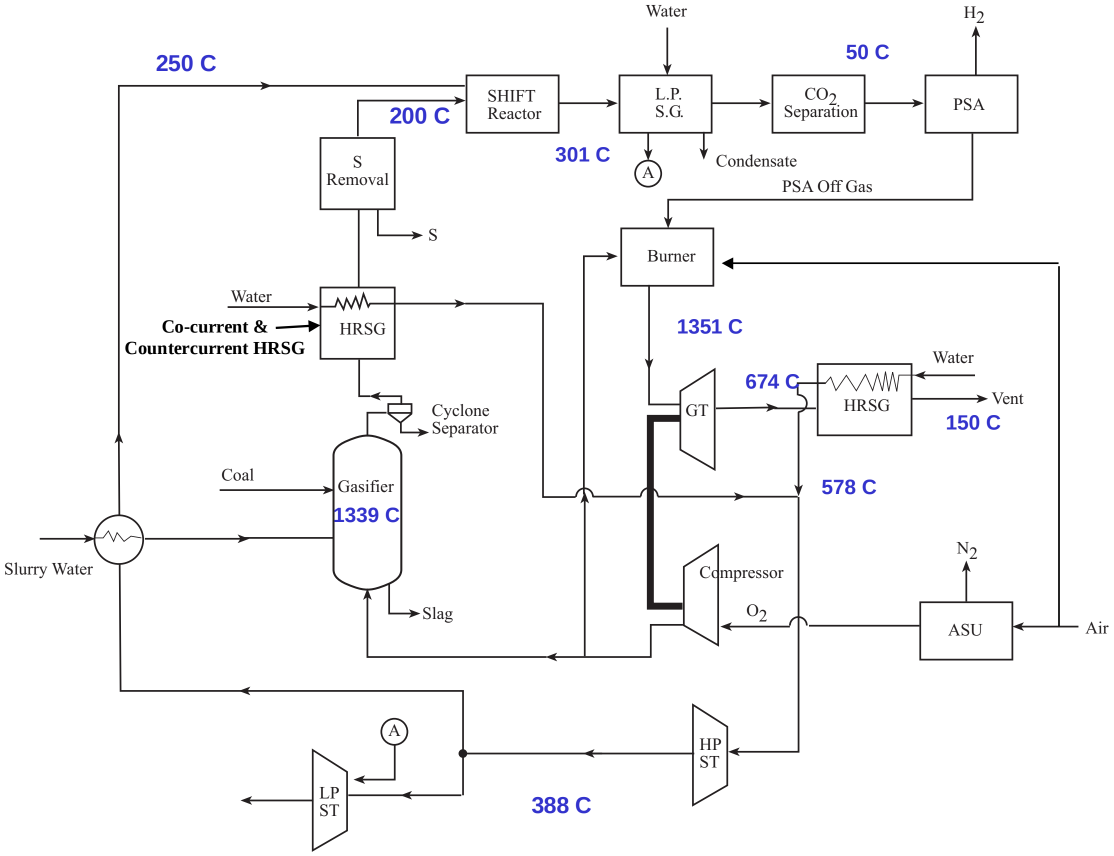


Figure 6. Process flow diagram for Advanced IGCC process for co-production of hydrogen and electricity (1:1) from coal.

In order to compare the two processes on a consistent basis, the efficiencies for both systems were calculated for a case involving co-production of H_2 and electricity (1:1). The ratio of H_2 to electricity produced can be varied by varying the temperature in the gasifier or by adjusting the recovery of the Pressure Swing Absorption (PSA) unit for H_2 separation. Table 5 shows the comparison of the 3-bed UFP technology and the advanced IGCC process.

Table 5. Comparison of the efficiencies for the advanced IGCC process and the UFP technology.

Process	**Advanced IGCC**	**UFP**
ASU, Compressors and Pumps, (%HHV Coal)	-19%	-18%
H_2 Purification, PSA, (%HHV Coal)	-0.2%	-0.2%
CO_2 separation, (%HHV Coal)	-1%	0%
Gas turbine, (%HHV Coal)	33%	31%
Steam Turbines, (%HHV Coal)	12%	20%
Net Electricity Produced, (%HHV Coal)	25%	33%
HHV of H_2, (%HHV Coal)	25%	36%
Efficiency	**49%**	**68%**
Equivalent Electrical efficiency	**43%**	**60%**

The process analysis shows that the UFP technology is more efficient as compared to the advanced IGCC process. Also the UFP system meets the DOE Vision 21 plant efficiency target of 60% electrical efficiency. The overall advantages of the UFP system over the advanced IGCC process are listed below:

1. The UFP technology does not require the use of an Air Separation Unit (ASU).
2. The UFP technology does not require the use of an additional CO_2 separation unit, due to its inherent CO_2 separation.
3. The UFP technology uses the higher-efficiency Bryton-Rankine cycle, while the advanced IGCC process uses the less-efficient Rankine cycle as well as the Bryton-Rankine cycle.

As a result of the above advantages, the efficiency of the UFP technology is higher than that of advanced IGCC process. This improved process efficiency also leads to competitive costs of electricity and H_2 for the UFP technology relative to the IGCC process.

Future process modeling and analysis work will include the following:

- Comparing the efficiency of the advanced IGCC and UFP technologies at various H_2 to electricity co-production ratios to identify the optimum operating conditions.
- Developing a dynamic model to analyze the start-up of the UFP technology to aid in development of an UFP technology control strategy.

PILOT PLANT ASSEMBLY (Task 6)

The assembly of the pilot plant has continued in the ninth quarter. Reviews of key system and subsystem designs have been conducted, and appropriate revisions made. The reactor design and solids transfer design were reviewed and updated during the ninth quarter, and the results are provided below.

Review of Pilot-Scale Reactor Design

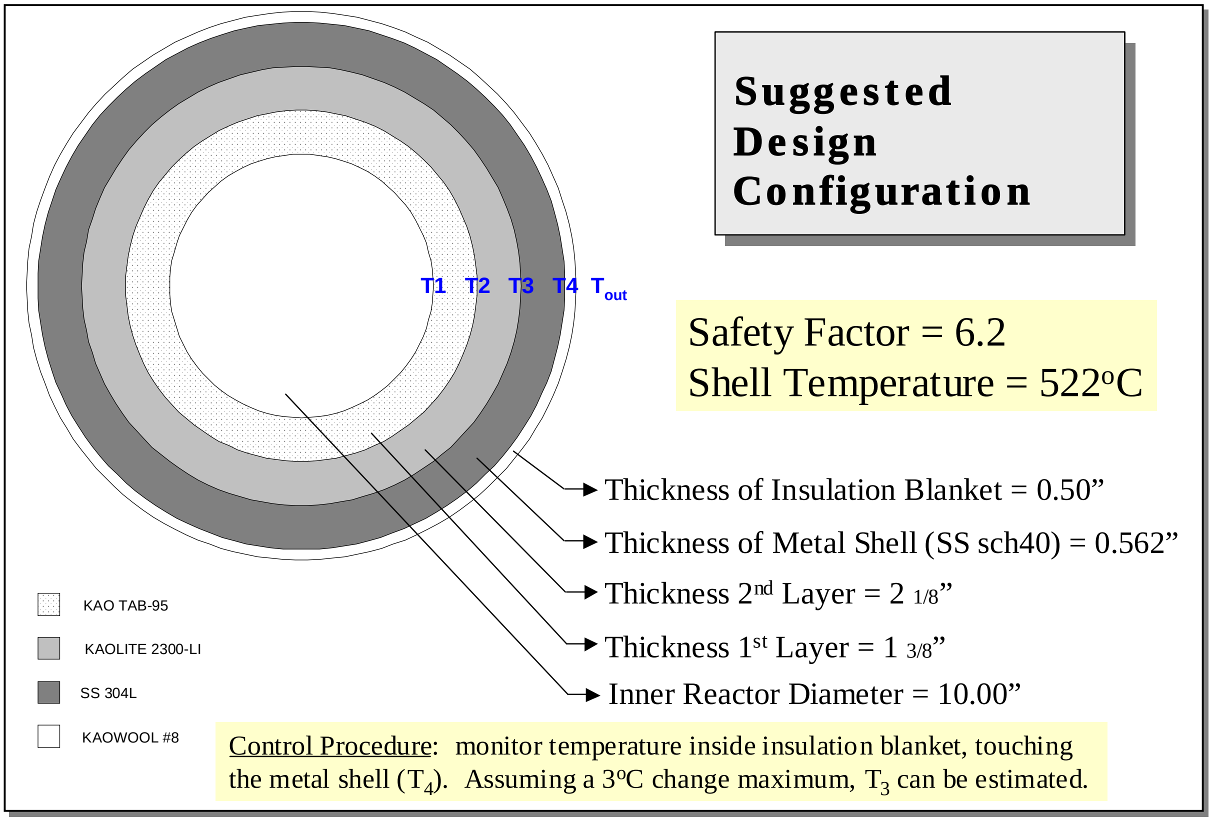
The preliminary design of the pilot-scale reactors was previously discussed in the second annual report (Oct 1, 2001 – Sep 30, 2002). This design was based on thermal and mechanical stress analyses using ASME code standards. The reactor design is a multi-layered structure, in which the innermost layer is a resistance abrasive material, the intermediate layer is a thermal insulating material, and the outermost layer (shell) is an alloy metal specified to withstand the high operating pressure.

An expanded team was assembled to conduct an internal reactor design review on November 11, 2002. Key points made at that meeting to improve feasibility and safety included the following:

- 1st layer material must be high-strength, abrasion resistant refractory.
- 2nd layer material must posses low k-factor (thermal conductivity).
- Metal shell (3rd layer) must be a low-cost, off-the-shelf alloy.
- Thickness of 1st layer should be a minimum of 1.5" to reduce the potential for crack formation caused by expansion/contraction, abrasion, and/or chemical attack.

Based on the reviewers' comments, the design was optimized utilizing the tools previously described in the second annual report; the Excel model with mechanical stress and heat transfer calculations and Design Expert 6.0. The optimized configuration, which meets all critical requirements and takes into account the recommendations of the design review team is shown in Figure 7. This design will be used for all three reactors.

Construction of the pilot-scale system is currently in progress. Casting of the internal refractory layers will be performed at GE EER, including refractory curing. Hydrostatic testing of the completed reactors will also be conducted at GE EER.



Suggested Design Configuration

Safety Factor = 6.2
Shell Temperature = 522°C

Thickness of Insulation Blanket = 0.50”
Thickness of Metal Shell (SS sch40) = 0.562”
Thickness 2^{nd} Layer = 2 1/8”
Thickness 1^{st} Layer = 1 3/8”
Inner Reactor Diameter = 10.00”

Control Procedure: monitor temperature inside insulation blanket, touching the metal shell (T_4). Assuming a 3°C change maximum, T_3 can be estimated.

Figure 7. Optimized pilot-scale reactor design configuration.

Solids Transfer Mechanism: Optimized Design

The transfer of solid bed materials between reactors is a critical part of the UFP technology, as it serves to transfer heat and regenerated reactants between reactors. As described in the second annual report, a full-size pilot-scale cold flow model was constructed to simulate the action of the solids transfer ducts and aid in the development of the solids transfer mechanism for the pilot-scale system. This cold flow model has provided valuable data regarding the effectiveness of different configurations. In the ninth quarter, experiments were conducted to optimize the initial solids transfer configuration. The three configurations tested and the optimization approach are described below.

The initial solids transfer configuration allowed solids to be drawn from the top of one reactor and delivered near the bottom of the next reactor. A solids carrier fluid was injected (air in this case) along the transfer duct to aid in solids transport. This configuration proved impractical because the head pressure at the bottom of the second bed was higher than the discharge pressure at the top of the first bed, requiring injection of an extremely large flow rate (greater than 50% of the fluidization gas flow rate) of transport gas for effective transport. In addition, a large portion of this carrier gas back-flowed to the first reactor.

In the second configuration, the solids flow was reversed; the solids were discharged from the bottom of one bed and delivered at a higher location into the next bed. Initially, the system was configured to deliver the solids slightly above the top of the next bed, which facilitated the task due to the lack of head pressure above the bed. The solid mass flow rates were measured by collecting the solids existing the transport duct into a vessel located atop a scale. Figure 8 is a schematic of this testing set-up.

Since the desired mass flow rate of solids (m_s) is known from the UFP technology modeling study, design specifications for the parameters L_{bed} (length of bed), F_g (flow of fluidization gas), F_c (flow of carrier gas), d_{or} (diameter of incoming duct), d_{ent}, and d_{pipe} (diameters of the delivery duct) were experimentally obtained by using this cold flow model.

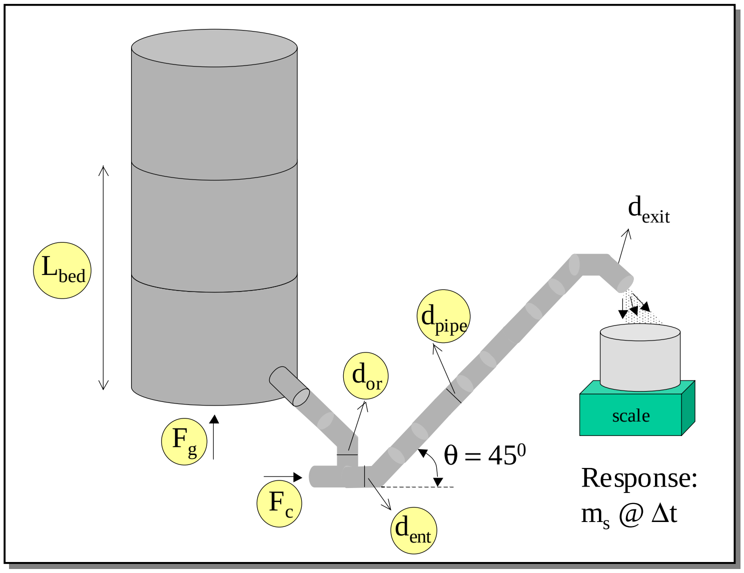


Figure 8. Schematic diagram of the second solids transfer configuration testing set-up: transfer from bottom of reactor to top of next reactor.

As a result of this configuration test, it was determined that the minimum flow of carrier gas (F_c) was approximately 50% of the fluidization flow. This amount of carrier is still rather large and would require an excessive amount of steam and thus an extremely large boiler. Another drawback of this configuration is that the delivery of solids above the top of the bed may pose problems such as: (a) the potential for reaction of char in the transfer duct (reducing process effectiveness and product gas residence times); (b) the potential for erosion of the reactor's refractory walls caused by blasting of solid particles at the opposite wall inside the reactor.

A third design configuration was developed, assembled and tested during the ninth quarter. This configuration integrated two modifications in order to address the potential problems identified previously. In the third modification, the carrier gas is injected vertically and the solids move upwards, (previously, the carrier gas was injected horizontally and the solids moved at an inline). Pneumatic transport theory suggests that carrier gas requirements are reduced when solids are moved vertically. After implementation of this change, a significant decrease in required carrier flow was observed. The gas flowrate for solids transfer was ~ 50% less than the flow rates required with the previous configuration.

The second fundamental alteration involved the solids delivery location in the bed. Process considerations dictated that the solids be delivered near the middle of the fluidized bed. Thus, the solids transfer duct was extended into the interior of the reactor and curved downward, facilitating delivery of solids near the middle of the reactor bed.

Experimental results show that this configuration allows solids to be delivered in the bulk of the fluidized bed as required. Measurements of the mass flow rates of solids for this configuration are in progress. Figure 9 is a schematic of the optimized solid transfer system.

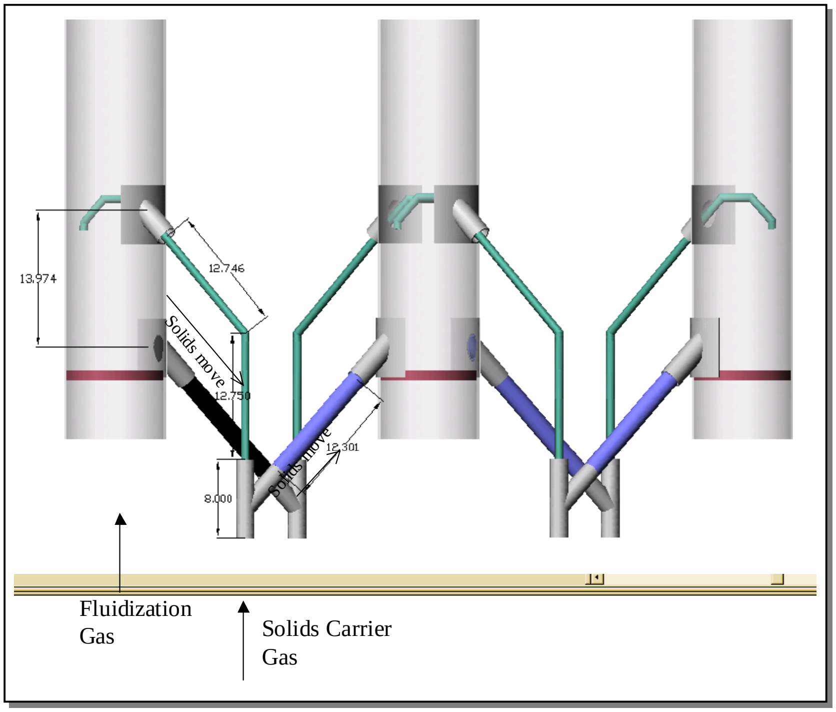


Figure 9. Schematic diagram of the optimized solids transfer mechanism.

SUMMARY AND CONCLUSIONS

Work conducted in this ninth quarter has focused on the assembly of the pilot plant, with additional experimental analysis being conducted at the lab and bench scales.

The lab-scale effort has included high temperature fluidized bed experiments to assess the impact of bed composition (OTM:CAM ratio) on coal gasification performance.

The bench-scale experimental efforts have focused on the completion of a detailed investigation into the behavior of OTM during the reduction and oxidation steps. The results of the designed experiments were used to develop a transfer function relating operating parameters to % OTM reduction and have already been used to identify achievable increased OTM reduction levels.

Process modeling of the UFP technology was performed using Aspen Plus version 11.1. The same modeling tool was utilized to model an advanced IGCC system and compare its process efficiency to the UFP system. The efficiencies for both systems were calculated for a case involving co-production of H_2 and electricity (1:1). Process analysis results indicate that the UFP technology is considerably more efficient as compared to the advanced IGCC process.

The pilot-scale assembly effort has continued, with reviews and modifications made to the reactor design and the solids transfer system design. In addition, the high-pressure compressor, and the slurry pump (for coal feeding) have been installed at the test site.

FUTURE WORK

Additional lab and bench-scale testing is planned to provide further insight into the rates and mechanisms of char burnout, CO_2 release and OTM reduction processes. Other continuing work on UFP technology development will include the assembly of the pilot-scale system, which will feature three fully integrated circulating, fluidized bed reactors. In addition, progress will be made on modeling tasks in support of pilot-scale system operation. Integral to all these efforts is the continuing analysis of the economics and competitiveness of the UFP technology based on experimental and theoretical findings. These tasks will aid in ensuring that the UFP system will meet the needs of the power generation industry both efficiently and economically.

Task 1 Lab-Scale Experiments – Fundamentals
Task 1 activities will include testing using the lab-scale high-temperature, high-pressure reactor and furnace. Kinetic tests involving coal, char, steam, air and combinations of oxygen-transfer material and CO_2 absorber material will be conducted. These experimental efforts will be closely coupled with the ongoing modeling efforts to ensure that the experiments will provide information useful in model validation.

Task 2 Bench-Scale Facility – Design/Assembly
This task has been completed.

Task 3 Bench-Scale Testing
Testing activities will focus on identification of optimized operating conditions and characterization of bed material performance and ash behavior. Results of these tests will be used along with lab-scale results to modify and validate kinetic and process models, as well as provide inputs for economic evaluation efforts.

Task 4 Engineering and Modeling Studies
Process and kinetic models will be further developed and validated using results from testing activities. These models will also be used to provide information for pilot plant design efforts. Specific tasks include: 1) comparing the efficiency of the advanced IGCC and UFP technologies at various H_2 to electricity co-production ratios to identify the optimum operating conditions and 2) developing a dynamic model to analyze the start-up of the UFP technology to aid in development of an UFP technology control strategy.

Results obtained from the preliminary economic assessment will be used for identification of critical operating parameters that have significant impacts on the cost of electricity and hydrogen, and for recognition of limiting conditions from an economic standpoint.

Task 5 Pilot Plant Design and Engineering
This task has been completed.

Task 6 Pilot Plant Assembly
Key subtasks include: finalizing the P&ID, finalizing the system layout, tracking ordered items, inspecting and testing manufactured parts, developing standard operating procedures, and designing the data acquisition interface. A plan will be developed for conducting shakedown

testing of subsystems as they are installed, with special attention devoted to the safety and emergency shutdown systems and their integration with all equipment.

Task 7 Pilot Plant Demonstration

After the pilot plant is assembled, extensive shakedown testing will be conducted, with modifications made as needed. The operational evaluation of the UFP technology will then proceed, followed by performance testing to identify the optimum H_2 yield that can be achieved with thorough analysis of the experimental data. A fuel flexibility study will be conducted to assess the impact of blending biomass fuels with coal.

APPENDIX A: DOE Meeting Agenda

Unmixed Fuel Processor (UFP) for Production of Hydrogen, Power & Sequestration-Ready CO_2
Program Review Meeting (DE-FC26-00FT40974) at GE Energy and Environmental Research Corp.
7 AM – 4:30 PM (PST), January 8, 2003, Irvine, California
Video Conference with NETL, Pittsburgh

AGENDA

Introductory Issues

7:00 Introductions (participants and agenda)
7:20 **(1)** Introduction to GE EER (Blair Folsom)
7:30 **(2)** Overview of GE’s H_2 Advanced Technology Corporate Initiative (Randy Seeker)
7:50 **(3)** Overview of GE’s hydrogen production programs (Vladimir Zamansky)

Unmixed Fuel Processor for Coal (UFP-Coal)

8:10 **(4)** Overview of the Vision 21 project (George Rizeq)
  Goals and Objectives
  Lab-scale and bench scale results
  Pilot plant design and construction
  Process modeling and economics
9:30 Break (Working lunch at NETL; GE EER lab tour)

Coordinated Programs

10:00 **(5)** UFP-NG and UFP-Oil (Ravi Kumar)
  Unmixed reformer - fuel cell program
  Unmixed reformer - refueling program
10:30 **(6)** Two-reactor concept for hydrogen production from coal (Vladimir Zamansky/Ravi Kumar)
10:50 **(7)** Efficient combustion of coal with OTM for electricity generation (Vladimir Zamansky/George Rizeq)
11:10 Discussion
11:30 Break (Working lunch at GE EER)

Discussion

12:00 **(8)** Technology development roadmap (George Rizeq/ Richard Koppang)
12:30 DOE vision and comments on large pilot scale technology demonstration plans (DOE participants)
1:20 Issues and next steps – discussion (All)
  Closing remarks for Pittsburgh participants

Test Site Tour (GE EER Test Site team)

2:00 Vision 21 bench-scale facility
  Vision 21 pilot system full-scale cold flow model
  Pilot scale reactors
  Pre-commercial 150 kWt prototype of unmixed reformer
  Combustion/gasification facilities

DOE Perspectives

3:30 DOE's perspectives and future plans on Vision 21 program (Larry Ruth/Victor Der)
3:50 Coal program roadmap - 20-years out (Larry Ruth)
4:10 Closing remarks

APPENDIX B: OTM Reduction Experimental Test Procedure and Set-up

Experimental Test Procedure

Step 1 Sample Setup

- Sample is weighed (CAM bed) and poured into inner-sleeve
- Reactor is sealed with inner-sleeve and pressurized with N_2 (bed remains fluidized with 100% N_2)

Step 2: Preconditioning (OTM Oxidation)

- Air is fed to bed (CAM)
- Oxygen feed concentration is reduced to ~ 7 vol% by mixing the air stream with N_2 (this reduces exothermic heat generation rate)
- End of preconditioning (dt_{cond} ~30min) concludes at 100% slip-through of O_2
- Bed remains fluidized with 100% N_2 feed (flow is increased)

Step 3: Process Setup

- Reactor is purged with N_2
- Feed is switched to steam

Step 4: OTM Reduction

- Either H_2 or CO is fed to the fluidized bed (fluidization gas is steam)
- Output stream is monitored for total dry-flow and dry-concentrations of CO, CO_2 and H_2
- End of reduction (dt_{rxn} ~1hr) concludes at 100% slip-through of either CO or H_2, feed gas is shutoff
- Bed remains fluidized with steam

Step 5: Process Setup

- Reactor is purged with N_2
- Steam is shutoff (100% N_2 fluidizes the bed)

Step 6:OTM Oxidation

- Air is fed to the bed (CAM)
- Oxygen feed concentration is reduced to ~ 7 vol% by mixing the air stream with N_2 (this reduces exothermic heat generation rate)
- End of oxidation (dt_{ox}~30min) concludes at 100% slip-through of O_2
- Bed remains fluidized with 100% N_2 feed

Step 7: Bed recovery

- Reactor is depressurized to ambient
- Inner-sleeve (contains bed) is removed from reactor and set aside to cool overnight
- Bed is recovered from inner sleeve and weighed

Experimental Set-up

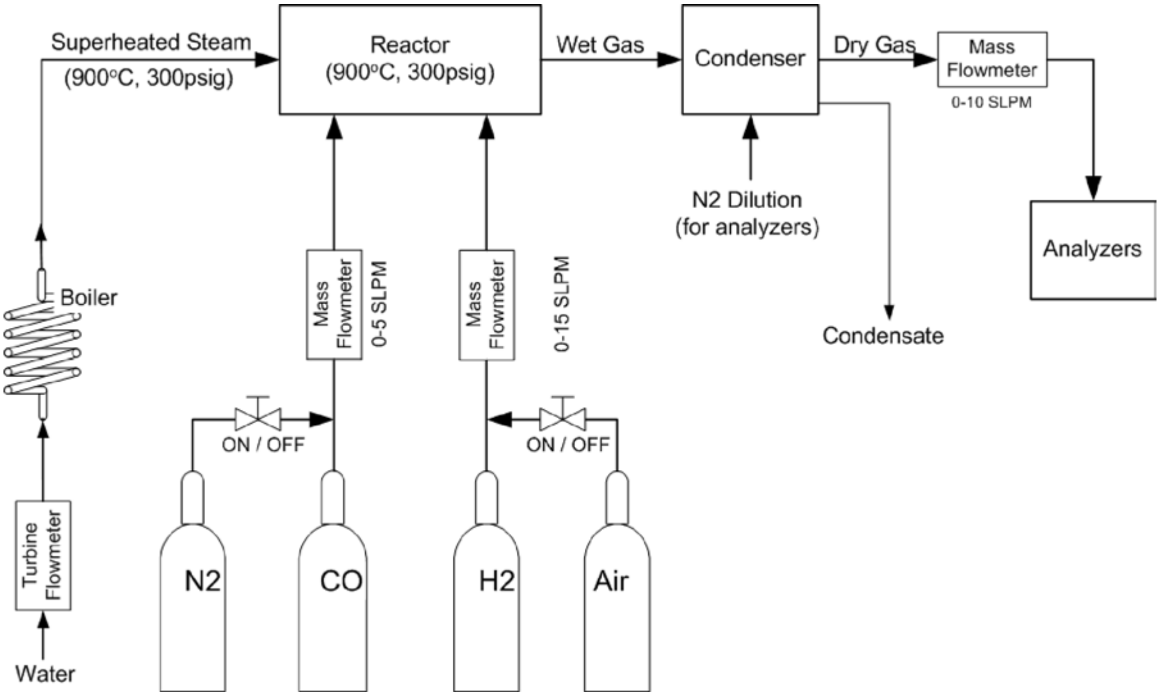


Figure B1. Experimental set-up.