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

Quarterly Technical Progress Report No. 14

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DISCLAIMER

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 Global Research 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 Global Research (prime contractor) was awarded a contract 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 Global Research, Southern Illinois University at Carbondale (SIU-C), California Energy Commission (CEC), and T. R. Miles, Technical Consultants, Inc.

In the UFP technology, coal and air are simultaneously converted into separate streams of (1) high-purity hydrogen that can be utilized in fuel cells or turbines, (2) sequestration-ready CO_2, and (3) high temperature/pressure vitiated air to produce electricity in a gas turbine. The process produces near-zero emissions and, based on ASPEN Plus process modeling, has an estimated process efficiency of 6 percentage points higher than IGCC with conventional CO_2 separation. The current R&D program will determine the feasibility of the integrated UFP technology through pilot-scale testing, and will investigate 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 experimental testing, modeling and economic studies to demonstrate the UFP technology.

This is the fourteenth quarterly technical progress report for the UFP program, which is supported by U.S. DOE NETL (Contract No. DE-FC26-00FT40974) and GE. This report summarizes program accomplishments for the period starting January 1, 2004 and ending March 31, 2004. 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-scale experimental testing, pilot-scale shakedown and performance testing, program management and technology transfer.

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EXECUTIVE SUMMARY

This is the fourteenth quarterly technical progress report for the UFP program, which is supported by U.S. DOE NETL (Contract No. DE-FC26-00FT40974) and GE. This report summarizes program accomplishments for the period starting January 1, 2004 and ending March 31, 2004. The report provides a description of the technology concept and a summary of program activities and accomplishments in lab-scale experimental testing, pilot-scale system shakedown and performance testing, program management and technology transfer.

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 is highly efficient relative to conventional electricity producing technologies and produces near-zero emissions. This R&D program will investigate operating conditions that maximize separation of CO_2 and pollutants from the vent gas, while simultaneously maximizing coal conversion to electricity efficiency and hydrogen production. The program integrates lab-, bench- and pilot-scale studies to demonstrate the UFP technology.

Work conducted in the fourteenth quarter of this program has focused on the shakedown testing and initial performance evaluation of the pilot plant, conducting additional experimental analysis of lab-scale systems, management and technology transfer.

The lab-scale effort in this quarter has included experimental investigations into OTM reduction behavior and bed material behavior at high temperatures. This information provides key results to guide experimental efforts and provide qualitative validation of process models.

UFP pilot plant system shakedown testing was conducted in this quarter to verify system functionality, identify baseline values for pressure drops and validate the solids transfer mechanism. The data acquisition and control system was tested and modified to meet operational demands. After completion of preliminary tests at atmospheric pressure, the top reactor flanges were replaced, and associated reactor exit piping and instrumentation were finalized. The reactors were then sealed and the system was leak-tested. Circulation at elevated pressures further validated the solids transfer mechanism, and reactor heat-up was conducted to validate the performance of the second-stage superheaters, as well as cure the reactor refractory. Plans were made for installation of the coal-feeding system above the reactors, with coal testing planned for early next quarter.

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 the ideal solution to many of this nation's energy needs if a satisfactory process for producing hydrogen from available energy resources such as coal and low-cost alternative feedstocks such as biomass is developed.

This UFP program addresses a novel, energy-efficient, and near-zero pollution concept for converting coal into separate streams of hydrogen, vitiated air, and sequestration-ready CO_2. The technology module comprising this concept is referred to as the *Unmixed Fuel Processor (UFP)* throughout this report. When commercialized, the UFP technology may become one of the cornerstone technologies to meet the DOE's future 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 coal feed 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 DOE future 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.

General Electric Global Research is the primary contractor for the UFP program under a contract from U.S. DOE NETL (Contract 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 the 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.
- Investigate 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 is partially gasified with steam in the first reactor, producing H_2, CO and CO_2. As CO_2 is absorbed by the CAM, 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.

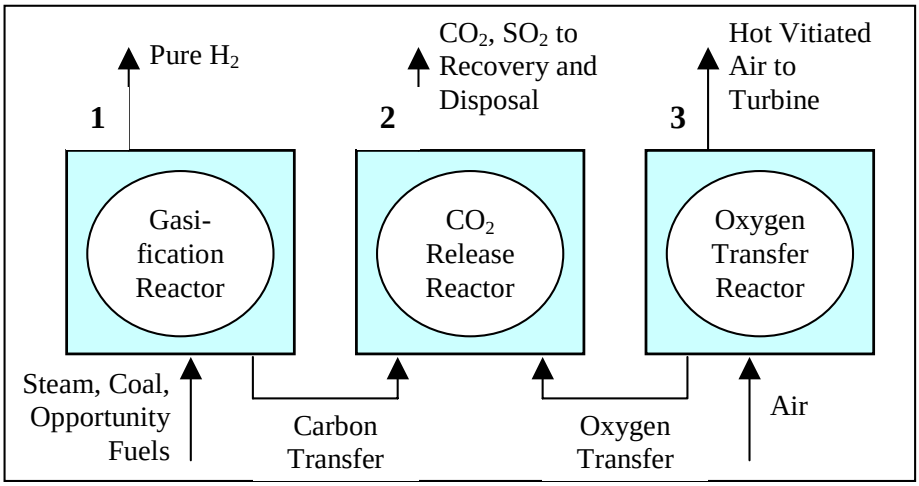

Figure 1. Conceptual design of the UFP technology.

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 3 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 system and increase the effectiveness of the bed materials.

PROJECT PLAN

Work on tasks planned for the UFP project (Table 1) was initiated in October 2000. The project was originally scheduled for completion in three years, but a nine-month no-cost extension that was granted by the DOE in August 2003 extended the completion date until June 2004. This extension was necessary due to delays in obtaining a South Coast AQMD permit to construct the pilot plant. 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.

MANAGEMENT AND TECHNOLOGY TRANSFER

Program planning activities have focused on meeting the objectives of the program as stated previously. GE Global Research 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 meets program objectives. This is accomplished through the use of 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

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

Program management activities also include the continuous oversight of program expenditures. This includes a 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 technical conferences.

During the last quarter, the GE Global Research UFP team held a review meeting with DOE representatives (Gary Stiegel, Stewart Clayton and Gil McGurl) on January 14, 2004 at the DOE offices in Germantown, MD. During the two-hour meeting, the UFP engineering team provided an overview of the UFP technology including progress to date and planned technology development activities. During the meeting, DOE and GE Global Research teams were engaged in fruitful discussions that helped in optimizing R&D work on the UFP tasks. The executive summary of that meeting is attached as Appendix A.

EXPERIMENTAL

During the last quarter, the pilot plant was subjected to process shakedown testing, which validated the functionality of the data acquisition and control system, second-stage superheaters, and the solids transfer mechanism. Additional results from the experimental facilities were obtained, analyzed and used to assess operating characteristics of the UFP. Laboratory-scale activities are being conducted by SIU in Carbondale, IL, while the pilot-scale system is located at the GE Global Research test site in Irvine, CA.

LABORATORY-SCALE TESTING

The primary objective of Task 1 is to perform a laboratory-scale demonstration of the individual chemical and physical processes involved in GE'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 this quarter included the use of TGA experimental results to produce kinetic data for the reduction of OTM by H_2 and CO. The reduction of OTM is a key UFP process that has been tested extensively by SIU. In addition, heat treatment testing has been conducted to characterize the behavior of CAM and OTM after exposure to high temperatures under either air or steam atmospheres. The samples were characterized for their propensity to agglomerate after heat treatment, and x-ray analyses were conducted to identify the formation of new phases.

Three series of experiments were conducted; the experimental matrix is detailed in Table 2. Tests conducted in the first test series made use of pure OTM and CAM supplied by Sigma Aldrich, a chemical supplier. For the second and the third series of experiments, OTM and CAM were combined with simulated coal ash and tested with either air (second series) or steam (third series). For these tests, GE supplied OTM and CAM that had previously been used for bench-scale testing, while the simulated ash was prepared using supplies obtained from Sigma Aldrich. Simulated coal ash was prepared by mixing 49% SiO_2, 49% Al_2O_3, 1.7% Na_2CO_3 and 1.3% K_2CO_3 (taking into account decomposition of sodium and potassium carbonate into sodium and potassium oxide at testing temperatures). Test series experimental details are provided below.

Series 1: Experiments were conducted in an open tube furnace. Mixtures of OTM and CAM of desired ratios were inserted into a preheated furnace and heated under an air atmosphere for 45 minutes at ambient pressure before being cooled in air. Samples were subjected to x-ray analysis after this heat treatment.

Series 2: Experiments were conducted in an open tube furnace. Samples of OTM, CAM and simulated ash were mixed in the desired ratios. These mixtures were then placed in a preheated furnace and heated under an air atmosphere at ambient pressure for the desired time (30 or 15 minutes). Next, the sample was cooled in air. Samples were subjected to x-ray analysis after this heat treatment.

Series 3: Experiments were conducted in a fluidized bed reactor. Samples of OTM, CAM and simulated ash were mixed in the desired ratios and placed in the reactor. These mixtures were heated under a nitrogen atmosphere to the desired temperature. Once the desired temperature was reached, a steam mixture was introduced (90% steam + 10% nitrogen) at ambient pressure for the desired time (30 or 15 minutes). The samples were then cooled in air and subjected to x-ray analysis.

Table 2. Test matrix for heat treatment of CAM and OTM.

First experimental series						
Run #	CAM (Sig.-Al.)	CAM-CO_2 (Sig.-Al.)	OTM (Sig.-Al.)	Flowing Gas	Temp (8C)	Time (min)
1.1	0	1	3	air	1100	45
1.2	0	3	1	air	1100	45
1.3	1	0	3	air	1100	45
1.4	3	0	1	air	1100	45
Second experimental series						
Run #	CAM (GE)	OTM (GE)	Ash (Sig.-Al.)	Flowing Gas	Temp (8C)	Time (min)
2.1	1	1	0	air	1050	30
2.2	1	1	0	air	1150	30
2.3	1	1	0	air	1150	15
2.4	1	1	0.2	air	1050	15
2.5	1	1	0.2	air	1150	15
2.6	1	1	0.2	air	1150	30
2.7	1	3	0	air	1050	15
2.8	1	3	0	air	1150	30
2.9	1	3	0.5	air	1050	30
2.10	1	3	0.5	air	1150	15
2.11	3	1	0	air	1050	15
2.12	3	1	0	air	1150	30
2.13	3	1	0.5	air	1050	30
2.14	3	1	0.5	air	1150	15
2.15	1	1	0	air	1050	15
2.16	1	1	0	air	1150	15
Third experimental series						
Run #	CAM (GE)	OTM (GE)	Ash (Sig.-Al.)	Flowing Gas	Temp (8C)	Time (min)
3.17	1	1	0.2	air	1050	30
3.18	1	1	0	steam	950	30
3.19	1	1	0	steam	750	30
3.20	1	1	0	steam	950	15
3.21	1	1	0.2	steam	950	15
3.22	1	1	0.2	steam	750	15
3.23	1	1	0.2	steam	950	30
3.24	1	3	0	steam	750	15
3.25	1	3	0	steam	950	30
3.26	1	3	0.5	steam	750	30
3.27	1	3	0.5	steam	950	15
3.28	3	1	0	steam	750	15
3.29	3	1	0	steam	950	30
3.30	3	1	0.5	steam	750	30
3.31	3	1	0.5	steam	950	15
3.32	1	1	0	steam	750	15
3.33	1	1	0	steam	950	15
3.34	1	1	0.2	steam	750	30

RESULTS AND DISCUSSION

LABORATORY-SCALE TESTING RESULTS

TGA experiments conducted previously were used to develop a kinetic model for OTM reduction. Figure 2 shows the impact of temperature on the extent of OTM reduction for a range of hydrogen concentrations. At 800°C, only at hydrogen concentrations approaching 10% is the OTM reduction complete (α=1) during the five-minute time interval shown. Meanwhile, at 900°C, complete OTM reduction is achieved at all concentrations shown, with increased H_2 concentrations causing reactions to proceed to completion more quickly. These results are encouraging, since the UFP's middle reactor will be operated at temperatures greater than 900°C to ensure CAM decomposition and CO_2 separation, thus ensuring that OTM reduction occurs more readily in the middle reactor, despite potential low H_2 and CO concentrations. Maximizing OTM reduction in the middle reactor minimizes the amount of oxidized OTM that could make it to the first (gasification) reactor where some H_2 may reduce the OTM and minimize H_2 concentration leaving the gasifier.

Heat treatment experiments were conducted according to the test matrix described previously in Table 2. Photographs of the CAM/OTM/Ash mixtures were taken both before and after testing to allow qualitative comparison of behavior. Baseline diffractograms were obtained using x-ray analysis of pure CAM and OTM samples. These baseline diffractograms provided increased confidence in interpreting results of x-ray analysis conducted after completion of tests from the test matrix.

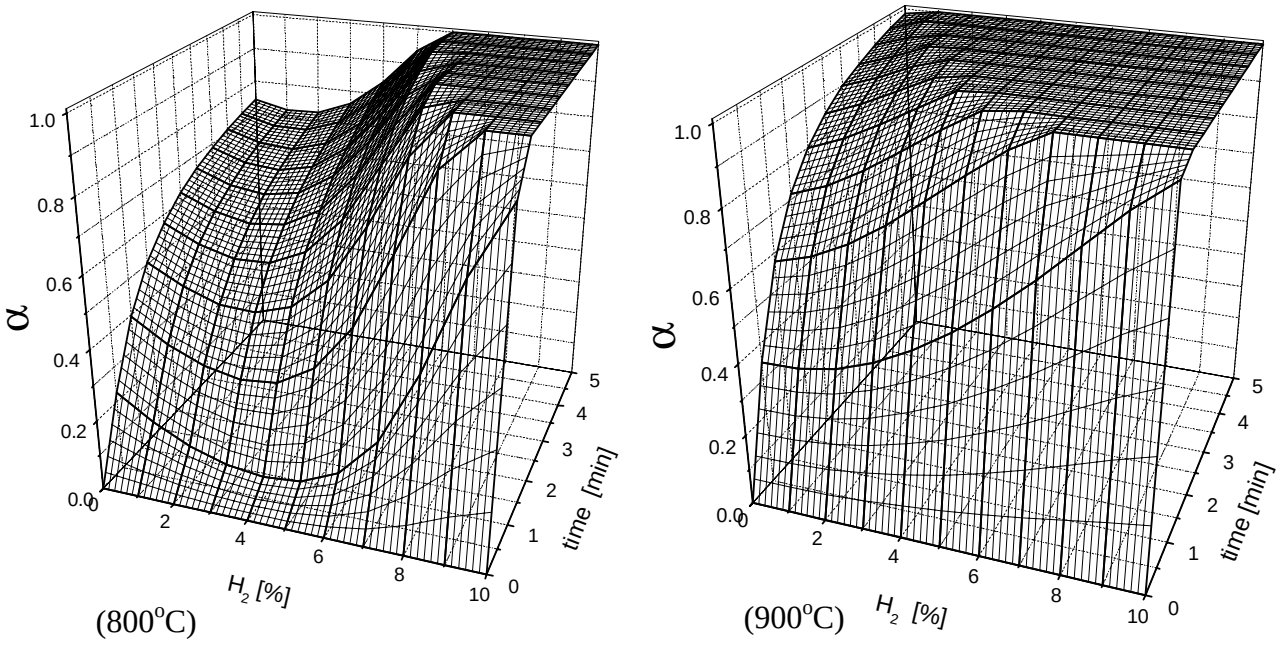

Figure 2. Kinetic modeling results showing the impact of temperature on conversion extent (α) over time for reduction of OTM with 0-10% H_2.

No significant agglomeration was observed in any of the samples after heat treatment. Only test 1.1, conducted with small particle-size pure OTM and CAM-CO_2, showed the formation of a complex CAM-OTM phase (see Figure 3). In all other tests, OTM and CAM present at the beginning of the test were identifiable via diffractogram after heat treatment. Testing conducted under a steam atmosphere as part of the third experimental series, led to formation of hydrated forms of CAM and OTM. No other forms of OTM or CAM were identified via x-ray diffraction.

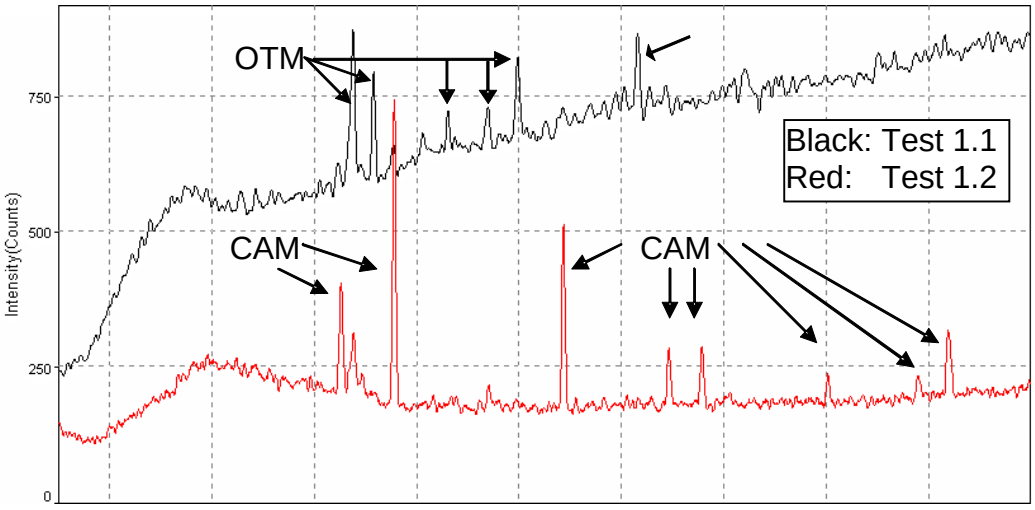

Figure 3. Diffractograms from experiments 1.1 and 1.2.

Heat treatment at temperatures 950°C and higher typically caused thermal decomposition of CAM-CO_2 to form CAM. During tests conducted at 7508C, decomposition of CAM-CO_2 to CAM was not always complete (some CAM-CO_2 was present in the diffractogram). Tests conducted with simulated ash had detectable levels of SiO_2 and Al_2O_3, but K and Na were present at concentrations below the detection limit of the x-ray diffraction analyzer.

These heat treatment results are encouraging since testing results suggest that CAM and OTM of the type used for the pilot plant do not agglomerate or form complex solid mixtures at the representative conditions tested. Additional work is planned to further assess behavior at typical operating conditions.

PILOT PLANT DEMONSTRATION

Process Shakedown Testing

Significant progress has been made toward completion of shakedown testing. Shakedown testing efforts have included the evaluation of the following key systems and subsystems:

- Data acquisition, safety and control system,
- Reactor fluidization and bed height measurement,
- Solids circulation.

A test matrix was developed for testing of reactor fluidization and solids circulation and bed heat-up. This test matrix is shown in Table 3, with the test type, key operating conditions, and key measurements noted for each test. During this quarter, shakedown testing was completed for tests 1-9, with reactor heat-up continuing into the next quarter.

Table 3. Process shakedown tests.

#	Test Type	Feed (Air or Steam)			Operating conditions		Reactor Top Flanges	Bed circulation	Key Measurements
		R1	R2	R3	T (^oC)	P (psig)			
1	dP of leg distributor plate (no bed)	Air	Air	Air	Ambient	14.7	Open	On	dP_leg
2	dP of bed distributor plate (no bed)	Air	Air	Air	Ambient	14.7	Open	Off	dP_reactor
3	dP of bed	Air	Air	Air	Ambient	14.7	Open	Off	dP_reactor, bed height
4	Verify bed movement	Air	Air	Air	Ambient	14.7	Open	On	dP_reactor, dP_leg
5	Bed circulation rate	Air	Air	Air	Ambient	14.7	Open	Varies	dP_leg, bed height
6	Leak test	Air	Air	Air	Ambient	60	Closed	Off	System pressure
7	Pressure uniformity across reactors	Air	Air	Air	200	30	Closed	On	Reactor pressure
8	Verify bed movement	Air	Air	Air	200	30	Closed	On	dP_reactor, dP_leg
9	Solids transfer rate	Air	Air	Air	200	30	Closed	On	dP_leg, bed height
10	Reactor heat-up	Stm	Stm	Air	800	30	Closed	On	Temperature

Baseline values for fluidization parameters were derived by measuring the pressure drop across each distributor plate with no bed in place. The three reactors each have a distributor plate, and each solids transfer leg also has a distributor plate. Each was characterized without a bed in place to provide a baseline value for comparison. In addition, baseline values of pressure drop across a well-characterized bed were also recorded to provide a basis for monitoring changes in pressure drop during process operation.

The solids transfer mechanism was validated first at atmospheric pressure, then at higher pressures. Baseline pressure drops were compared to the pressure drops measured during solids transfer. In addition, by altering the solids transfer flow selectively, it was possible to cause accumulation of bed solids in one reactor. Testing the responsiveness of solids transfer allowed the calculation of transfer rates. These tests were repeated at elevated pressures after the top flanges were put in place.

Operation at elevated pressures required the minimization of leaks from the system. A leak test was conducted to identify system leaks prior to testing at elevated pressures. The responsiveness of the valves controlling reactor pressure was evaluated using manual control of the valves, with good results. Characterization tests were grouped to allow all atmospheric pressure testing to be completed before conducting tests with the top flanges closed. When the top flanges were closed, the piping of reactor exit lines was completed, and the instrumentation completed and tested. Figure 4 shows the tops of the reactors with the top flanges in place, as well as the piping and instrumentation.

Figure 4. Photo of installed top reactor flanges as well as reactor exit piping and instrumentation.

Figure 5. Custom insulation of steam manifold, steam input lines and (inset) reactor flange.

During this quarter, custom insulation was installed on the bottom reactor flanges and the steam manifold and steam input lines. This custom insulation (Figure 5) is durable and weatherproof and reduces heat loss as the steam flow exits the superheater, is divided in the steam manifold, and travels to the second-stage superheaters prior to being fed to the reactors.

Data Acquisition, Safety and Control System

The pilot-scale system has been designed to allow the control of operating parameters within design limits and the monitoring and recording of key process variables and performance indicators. The safety system was tested to ensure safe operation of the pilot plant. Over-temperature and over-pressure alarm limits were set for each thermocouple and pressure transducer. Limits were also set for other monitored instruments such as differential pressure transducers. A special alarms screen allows the exact location and type of alarm to be quickly identified. Select temperatures and pressures automatically cause corrective action, such as a valve opening or closing. This system has been tested and validated by temporarily lowering alarm limits to cycle through alarm states.

The LabVIEW virtual controllers and the interactive user interface were tested and modified to provide desired operability. The user interface includes several different screens for controlling and monitoring the process. Figure 6 is the main control screen, which has controls for all of the on/off and analog control valves. This screen also has a numerical display of all the data acquired. Other screens include real-time plots of reactor temperature, CEMS gas concentrations, and bed heights. The program designer worked with system operators to provide a monitoring screen with key numerical measurements displayed to indicate their relative location on a diagram of the system, as shown in Figure 7. This arrangement facilitates a greater intuitive understanding of the interaction of temperature, pressure, flow rate, pressure drop and bed height for each reactor as well as for the system as a whole.

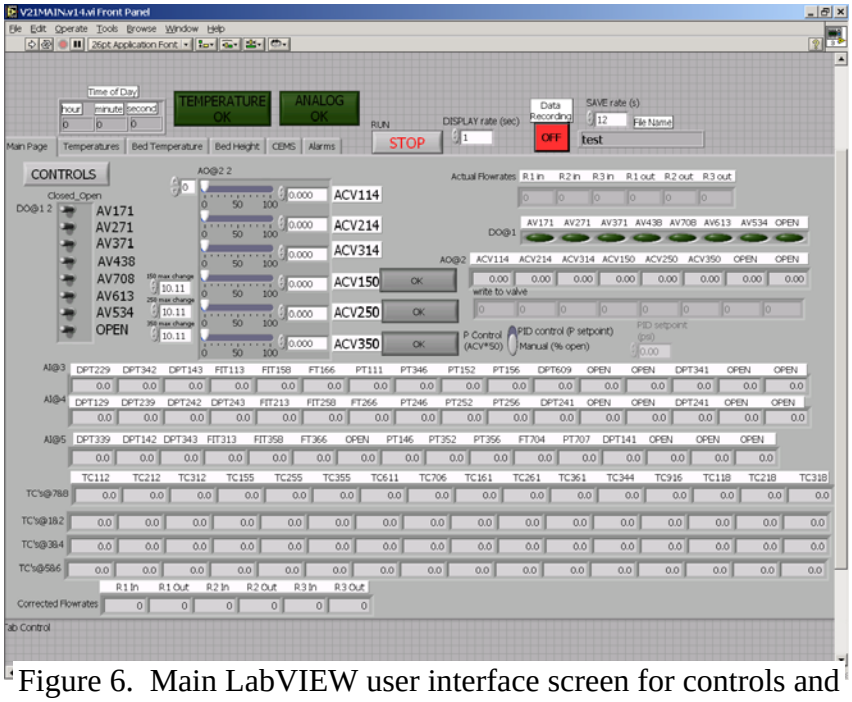

Figure 6. Main LabVIEW user interface screen for controls and data acquisition.

System shakedown testing was conducted using the LabVIEW program to control the system as well as record all monitored data. The program was modified to allow data to be saved at a different rate than the data acquisition rate to prevent the accumulation of extremely large files during extended heat-up runs associated with curing the reactor refractory. Temperature measurements were analyzed to monitor the rate of bed heat-up as well as the extent of heat loss. Operational experience was also gained in the control of the main reactor pressures, which was initially performed manually. Since all three reactors are interconnected via solids transfer ducts, it is important to maintain the same pressure in all three reactors.

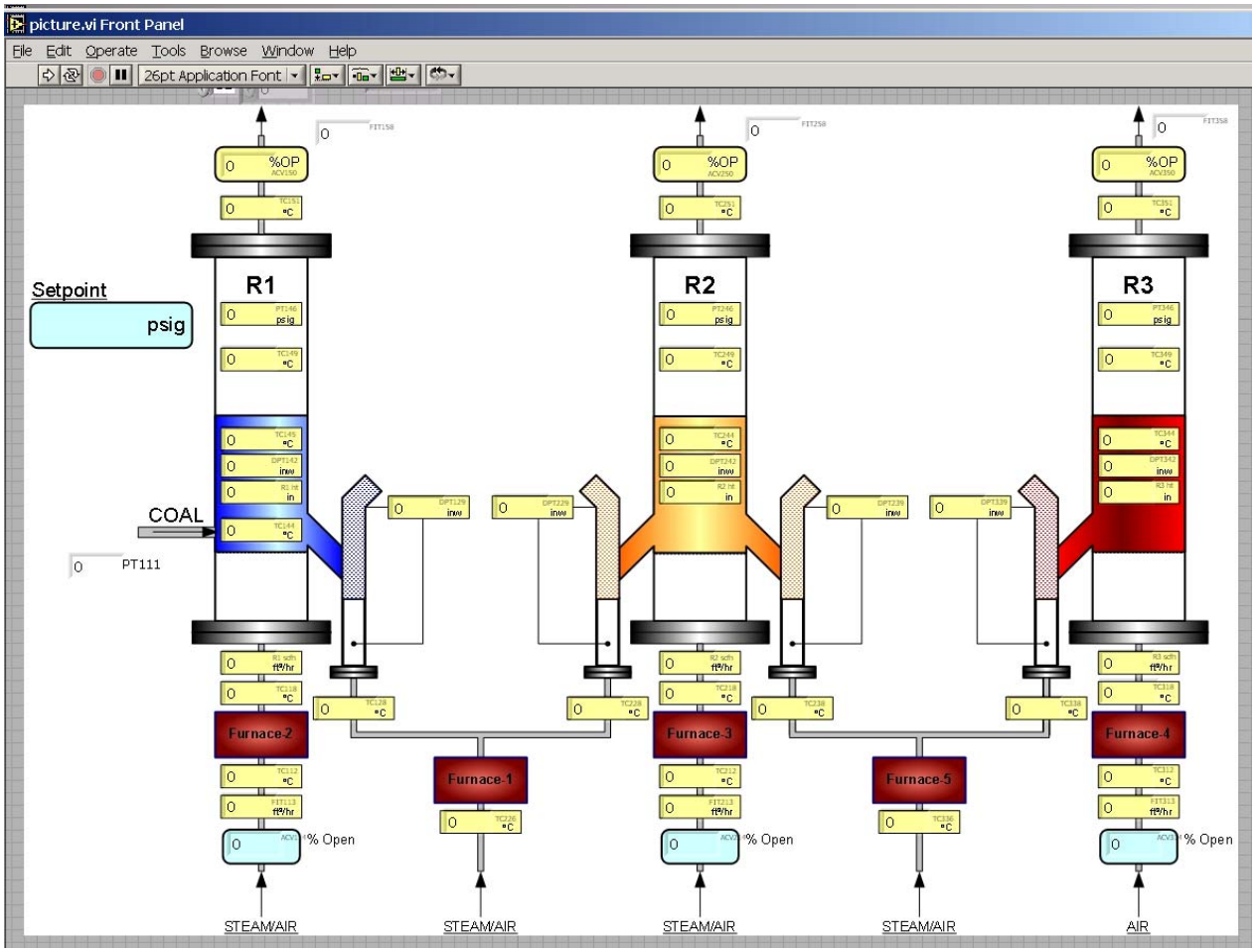

Figure 7. LabVIEW data acquisition screen with data measurements displayed to indicate their relative location on a diagram of the system.

Reactor Fluidization and Bed Height Measurement

During shakedown testing, the fluidization of the OTM/CAM beds in each reactor was verified visually during atmospheric testing. The system behaved as expected from the results of cold flow fluidization modeling. The method for measuring bed height was also validated. This method is shown in Figure 8, and makes use of two differential pressure measurements for each reactor. These measurements are used in the equation shown, which makes use of the location of the differential pressure taps to estimate bed height based on density differences. Bed heights were measured directly via measurements taken with a long pole lowered into the reactors while the reactor tops were open. The bed height measurements compared favorably with the calculated values.

$$L_{bed} = \frac{DPT142}{DPT143} \times H_1 + H_2$$

H_1 = 9 in

H_2 = 4 in

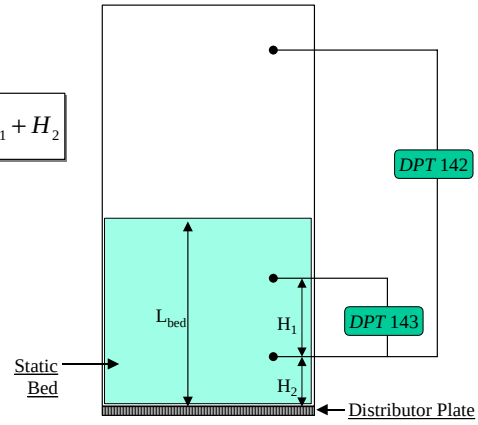

Figure 8: Approach for measuring fluidized bed

Solids Circulation

The circulation of bed materials is a key mechanical aspect of the UFP process. During initial testing of the solids circulation system, the bed heights remained steady. Visual monitoring of the transfer exit inside the reactor showed a pulsed transfer of bed materials into each reactor. Indirect bed height measurements were conducted during tests with bed circulation, and these tests showed that bed levels could be maintained over time. Figure 9 shows the bed heights calculated during 140 minutes of testing. The heights stayed relatively steady throughout the duration of the test. The figure also shows the differential pressures measured in each reactor, which are only slightly lower than the predicted differential pressure of 25.3 inches of H_2O.

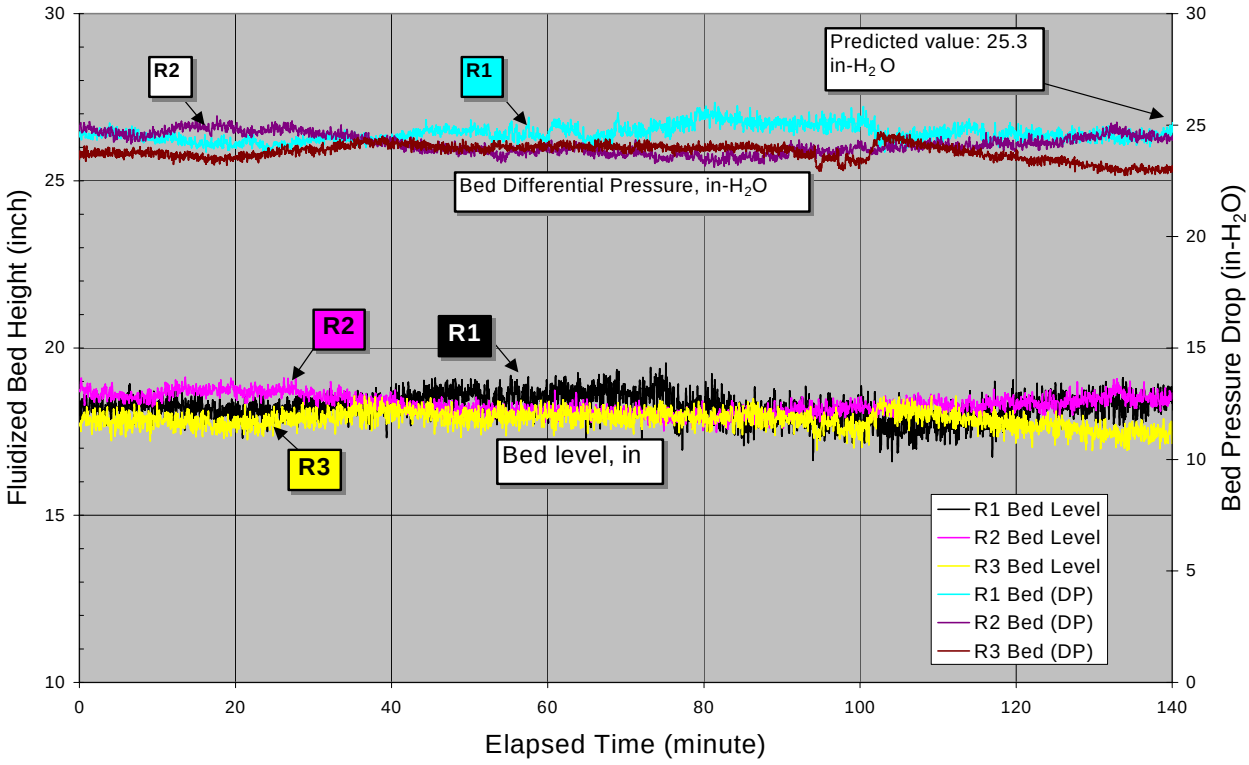

Figure 9. Performance curves during 140 minutes of steady solids circulation

During one shakedown test, the bed heights were manipulated to provide evidence of the rate of solids transfer. Figure 10 shows the increase in R3 bed height due to solids accumulation when transfer from R3 to R2 was temporarily halted. Since transfer from R2 to R3 continued, the increase in bed height is directly proportional to the rate of solids transfer from R2 to R3. During this period, a flow rate of 1.26ft^3/hr was estimated.

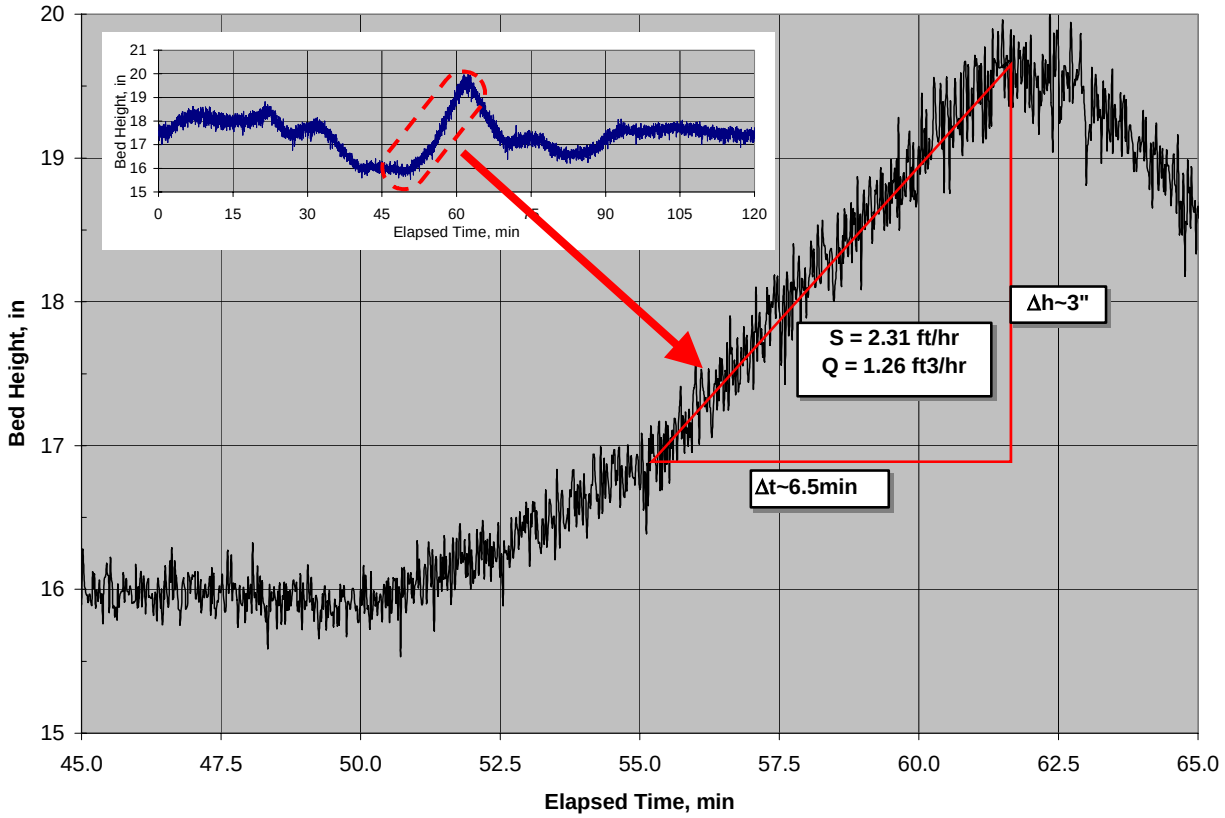

Figure 10. Rate of accumulation of bed materials in R3, as measured by bed height, when transfer of bed materials from R3 to R2 was temporarily halted.

Since the solids transfer takes place in a closed system, a bed height increase in one reactor must be compensated by a decrease in bed height in another reactor. During one test, a series of solids transfer system parameters were manipulated to characterize the ability of system operators to control bed heights. Figure 11 shows the bed heights for all three reactors while solids transfer flows were either turned on or off. The symmetric nature of bed height increases and decreases offers further validation of the bed height measurement method, as well as the consistency of the solids transfer rates. During the test shown in Figures 10 and 11, the total bed height (the sum of the three reactor bed heights) had a standard deviation of only 0.3 inches, while the individual reactor bed heights had standard deviations of 0.8. Although the bed heights were being manipulated, the sum of all bed heights remained relatively steady throughout the duration of the test, as shown in Table 4.

Table 4. Measurements of bed heights during two-hour test: Variation in data.

Bed Height	R1	R2	R3	Total
Average	17.6	16.5	17.4	51.5
Maximum	20.1	18.6	20.0	52.5
Minimum	15.4	14.5	15.5	50.0
Standard deviation	0.8	0.8	0.8	0.3

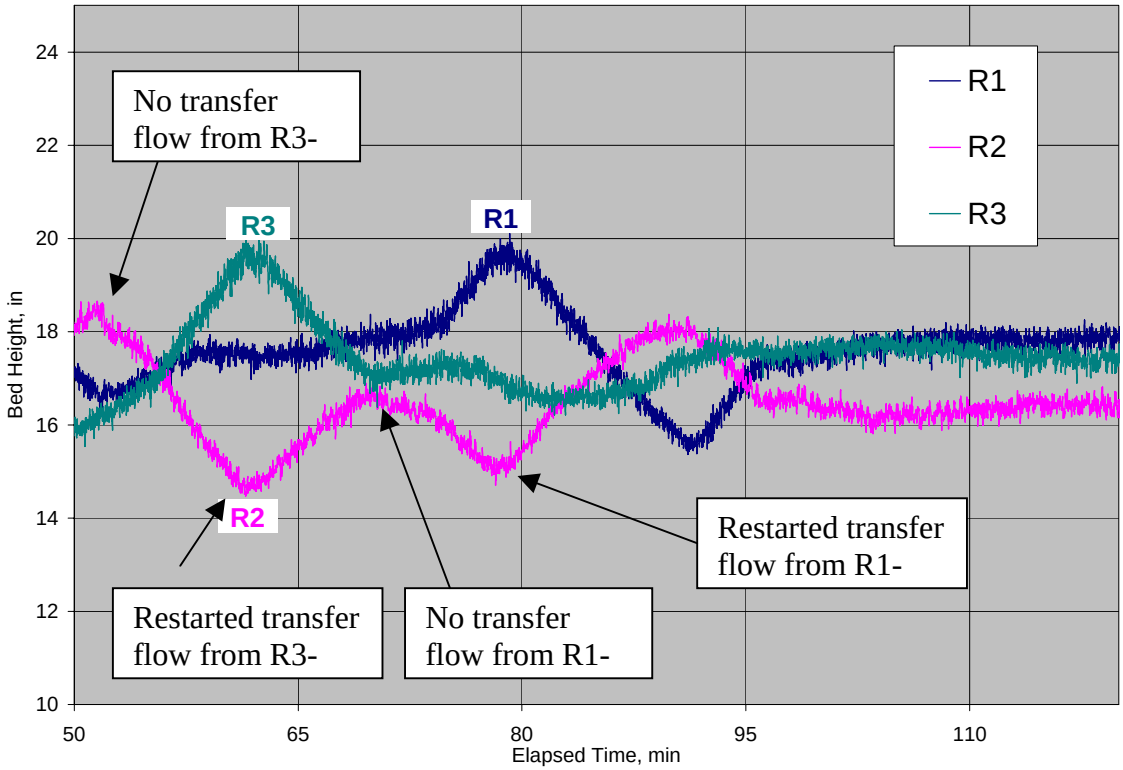

Figure 11. Manipulation of solids transfer flow and impact on bed height.

Boiler, Superheater and Second Stage Superheater

The boiler and superheater were tested, and associated water conditioning equipment was also installed and tested. In addition, the second-state superheaters were tested extensively during curing of the reactor refractory with air heated by the superheaters. Initial problems with excessive heat loss were identified as related to the incomplete curing of the reactor refractory. After several extended heat-up periods, increased temperatures were achieved in the reactors, and testing with superheated steam is planned for the next quarter.

Performance Testing

The key distinction between shakedown testing and performance testing is the use of coal in the first reactor. Much of the shakedown testing focuses on mechanical aspects of system design, but the heart of the process is the gasification of coal and its ability to drive the OTM oxidation-reduction cycle that generates heat for the process. Testing will be conducted first at low pressure to validate system operation and safety before conducting higher-pressure tests with coal slurry feed. Initial tests will focus on establishing baseline performance at conditions identified by process modeling.

CONCLUSIONS

Work conducted in the fourteenth quarter has focused on validating the operability of the pilot plant prior to testing with coal. In addition, lab-scale experiments continue to characterize OTM behavior with respect to reduction reactions and OTM/CAM bed behavior at elevated temperatures.

Significant progress was made in the fourteenth quarter. The pilot-scale system has been tested for system operability. All systems have now been validated, and the system is nearly ready for UFP performance testing with coal feed. The pilot plant system (Figure 12) has been designed to further establish the feasibility and performance of the UFP system. Lab and bench-scale experiments, as well as process modeling efforts have supported the pilot plant design efforts and will be used to support optimization of pilot plant operation through targeted testing of key UFP processes individually. The progress made to date has established the chemical (at bench-scale) and mechanical (at pilot-scale) feasibility of the UFP concept, and planned experimental efforts aim to further establish the UFP process as a key technology that meets future power generation needs economically, efficiently and environmentally.

Figure 12. UFP pilot-scale system and auxiliary systems.

FUTURE WORK

Future work on UFP technology development will include the operational evaluation of the UFP process at pilot scale. Additional lab-scale testing will be conducted to provide further insight into the rates and mechanisms of char burnout, CO_2 release and OTM reduction processes. In addition, progress will be made on the kinetic 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.

REFERENCES

(no references)

LIST OF ACRONYMS AND ABBREVIATIONS

AQMD	Air Quality Management District
CAM	CO_2 Absorber Material
CEC	California Energy Commission
CEMS	Continuous Emissions Monitoring System
CTQ	Critical to Quality
DFSS	Design for Six Sigma
GC	Gas Chromatograph
IGCC	Integrated Gasification Combined Cycle
NETL	National Energy Technology Laboratory
NTI	New Technology Introduction
OTM	Oxygen Transfer Material
R1	Reactor 1
R2	Reactor 2
R3	Reactor 3
SIU-C	Southern Illinois University – Carbondale
TGA	ThermoGravimetric Analyzer
UFP	Unmixed Fuel Processor
U.S. DOE	United States Department of Energy

APPENDIX A: Executive Summary of Jan. Review Meeting

Unmixed Fuel Processor for Production of Hydrogen, Power and Sequestration-Ready CO_2 (DE-FC26-00FT40974)

A program review meeting between U.S. DOE and GE Global Research (GEGR) representatives was held at DOE's offices in Germantown, MD on Wednesday, January 14, 2004. The goals of the meeting were to review GEGR's progress on the Unmixed Fuel Processor (UFP) program and discuss related technology development plans. Six U.S. DOE personnel attended the meeting:

- Stewart Clayton – IGCC Portfolio Manager, Office of Fossil Energy
- Victor Der – Director - Power Systems Division, Office of Fossil Energy
- Joseph Giore – Office of Fossil Energy
- Darren Mollot – Planning and Environmental Analysis, Office of Fossil Energy
- Edward Schmetz – Portfolio Manager, Transportation, Fuels & Hydrogen
- Robert Wright – Power Systems Portfolio Manager, Office of Fossil Energy

GEGR personnel attending included:

- George Rizeq – Project Leader, Fuel Conversion Lab
- Mike VanDerwerken – Business Development Manager
- Vladimir Zamansky – Manager, Fuel Conversion Lab

The two-hour meeting, see agenda below, included four GEGR presentations and discussions with DOE personnel focused on program review and UFP program continuation plans.

Agenda – UFP-Coal: DOE Project Review Meeting, January 14, 2004

- 09:45 AM – Arrive
- 10:00 AM – GE Global Research (GEGR) overview and goals (M. VanDerwerken)
- 10:15 AM – GEGR Fuel Conversion Lab capabilities & UFP process overview (V. Zamansky)
- 10:30 AM – Vision 21 UFP project update (G. Rizeq)
  - UFP development status and Irvine meeting update (10/16/03)
  - Recent progress on pilot plant assembly, component shakedown, and modeling
  - Plans for initial system shakedown and basic operability assessment
  - Performance assessment of key technical issues important for technology development
    - Basic system operability & solid materials transfer between reactors
    - H_2 production and inherent CO_2 separation
    - Absence of showstoppers
- 11:15 AM – Plan for continued UFP technology development (G. Rizeq)
  - Identify specific objectives and performance goals for phase I program continuation
  - DOE and GE funding commitment
  - GE long-term commercialization plan
    - Commercialize products/technologies that meet customer needs within economic and environmental constraints.
    - UFP technology meets both DOE and Customer goals and needs.
    - UFP technology development is being closely monitored by GE Energy CEO, John Rice, and has been well received by the power generation community at recent conferences.
  - Team
- 11:30 AM – DOE input and discussion
- 12:00 PM – Adjourn

GEGR's recent progress on the UFP project and further development steps were discussed in detail during the meeting. Despite the delay in obtaining a South Coast AQMD permit to "construct and operate" the UFP pilot plant, the GEGR team continued to make progress towards meeting program objectives particularly in assembly of the pilot plant, shakedown of key subsystems, process modeling, and drafting plans for system shakedown, initial testing, and criteria evaluation tests.

Key presentation topics included:

- Criteria for successful completion of the current UFP program: (1) basic system operability & solid materials transfer between reactors, (2) H_2 production and inherent CO_2 separation, and (3) absence of showstoppers. The system and its subsystems will be operated for about 80 hours in February-March 2004.
- Suggested objectives of continuing the UFP program: (1) identify final disposition of pollutants, (2) characterize attrition of bed, (3) find conditions for long-term operation, and (4) identify key data to help with validation and scale-up.
- Recent process analysis results, including comparisons of efficiency and cost with IGCC systems (current process models have been updated to provide comparison of UFP with IGCC co-producing H_2 with CO_2 separation).
- GE and DOE funding commitment and team.

Discussion topics and recommendations for future activities included:

- Victor Der suggested that Mike VanDerwerken contact California Energy Commission (CEC) and entice them to participate in the UFP development program and potentially share in providing funds for continuation of the program. The UFP is a fuel flexible technology designed to utilize renewable fuels, such as biomass, in addition to coal, that might be of interest to CEC.
- Victor Der suggested we present results on potential agglomeration of the bed material. Some data was obtained in the current project at bench scale. New experimental information on agglomeration and risk mitigation steps should be found and analyzed in further process development.
- Victor Der also suggested considering, as a step in technology development, demonstration of the process in a slipstream of an existing plant.
- Stewart Clayton suggested that the GEGR team develop a more detailed project implementation plan for the UFP continuation program including extended testing and optimization of the pilot plant. This plan should build on what was presented in the meeting including details on types of tests, objectives, and duration. The project continuation plan should also include criteria evaluation tests planed to be performed in the current project that ends in June 2004. The document would then be presented to DOE (both to Germantown and NETL teams) for evaluation.
- Ed Schmetz suggested adding overview of all issues in technology development and how the GEGR team plans to address them.
- Stewart Clayton, with concurrence of other DOE meeting participants, suggested a follow-up meeting at NETL in Pittsburgh. Participants will include GEGR and the DOE

Germantown and NETL teams (including NETL Product Managers responsible for coal-to-hydrogen and CO_2 sequestration). The follow-up meeting objectives would be to present recent results from the UFP pilot plant tests and to discuss UFP program continuation including contractual issues (for two-year extension) and additional funding commitments from DOE, GE, and CEC (if possible).

- The existing contract for the Vision 21 UFP program is to be examined to find out if an extension of this program for two more years with additional funding is possible. The GEGR Project Manager will contact Kamal Das (DOE Project Officer) and William Mundorf (DOE Contract Officer) to explore this possibility once additional DOE/GE funds are granted.

In summary, the DOE team was generally pleased with progress to date on the UFP project and anxious to see future development milestones, particularly the successful operation of the pilot-scale system. The DOE team provided insight into current DOE policies and goals (H_2 production and power generation from coal with CO_2 separation) as met by the UFP technology and possible routes to continued funding of UFP development.