**Fuel-Flexible Gasification-Combustion Technology for Production
of H₂ and Sequestration-Ready CO₂**

Phase II

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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 Global Research has developed an innovative fuel-flexible Unmixed Fuel Processor (UFP) technology to produce H₂, power, and sequestration-ready CO₂ 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 was awarded a contract from U.S. DOE NETL to develop the UFP technology. Work on the Phase I program started in October 2000, and work on the Phase II effort started in January 2005.

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 CO₂, and (3) high temperature/pressure vitiated air to produce electricity in a gas turbine. The process produces near-zero emissions with an estimated efficiency higher than IGCC with conventional CO₂ separation. The Phase I R&D program established the feasibility of the integrated UFP technology through lab-, bench- and pilot-scale testing and investigated operating conditions that maximize separation of CO₂ and pollutants from the vent gas, while simultaneously maximizing coal conversion efficiency and hydrogen production. Phase I integrated experimental testing, modeling and economic studies to demonstrate the UFP technology.

The Phase II effort will focus on three high-risk areas: economics, sorbent attrition and lifetime, and product gas quality for turbines. The economic analysis will include estimating the capital cost as well as the costs of hydrogen and electricity for a full-scale UFP plant. These costs will be benchmarked with IGCC costs for plants of similar size.

Sorbent attrition and lifetime will be addressed via bench-scale experiments that monitor sorbent performance over time and by assessing materials interactions at operating conditions. The product gas from the third reactor (high-temperature vitiated air) will be evaluated to assess the concentration of particulates, pollutants and other impurities relative to the specifications required for gas turbine feed streams.

This is the seventeenth 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 Phase II period starting January 1, 2005 and ending June 30, 2005. 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 process modeling, scale-up and economic analysis.

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EXECUTIVE SUMMARY

This is the seventeenth quarterly technical progress report for the UFP program, which is supported by U.S. DOE NETL (Contract No. DE-FC26-00FT40974) and GE. This is the first technical report of the Phase II program which will address three major technology risks through analysis and experiments: economic feasibility, sorbent attrition/lifetime, and product gas quality relative to gas turbine requirements.

This report summarizes program accomplishments for Phase II effort starting January 1, 2005 and ending June 30, 2005. The report provides a description of the technology concept and a summary of program activities and accomplishments in process modeling and scale-up for economic analysis.

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 CO₂, 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.

During this quarter, the work on the UFP economic analysis was initiated. The CAPEX, cost of H₂ and cost of electricity will be estimated for a commercial scale UFP system and will be compared with conventional IGCC technology. Worley Parsons will carry out the economic analysis for 3 cases: Base case IGCC, Polygen IGCC, and UFP.

Scale-up tools were developed for the conceptual design of a UFP-based full-scale system. Aspen software was used to develop material and energy balances and efficiency assessments for fully integrated power generation systems. MathCad and TechPlot software was used to scale up the UFP system from pilot-scale to commercial-scale with detailed reactor designs and equipment specifications, which provide the basis for economic analysis of the commercial-scale three-reactor UFP system.

INTRODUCTION

Projections of increased demands for energy worldwide, coupled with increasing environmental concerns have given rise to the need for new and innovative technologies for coal-based energy plants. Incremental improvements in existing plants will likely fall short of meeting future capacity and environmental needs economically. The objective of this Phase II research and development program is to further investigate GE's novel Unmixed Fuel Processor (UFP) technology; quantifying the economic benefits and characterizing the technical risks associated with sorbent attrition/lifetime and product gas quality through experimental evaluation at both bench and pilot scales, as well as through engineering and modeling efforts.

The UFP technology is a new, energy-efficient, and near-zero pollution concept for converting coal into separate streams of hydrogen, vitiated air, and sequestration-ready CO₂. 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 coal leaves the UFP module as hydrogen and the rest as high-temperature, high-pressure gas that can produce electricity in a gas turbine. The combination of producing hydrogen and electricity is highly efficient, meets all objectives of DOE future energy plants, and provides product flexibility; the ratio of hydrogen to electricity production can be adjusted to match changing demand.

GE Global Research is the primary contractor for the UFP program under a contract from U.S. DOE NETL (Contract No. DE-FC26-00FT40974). This project integrates bench and pilot-scale studies with process and economic modeling to demonstrate the UFP technology. 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:

- Establish the economic feasibility and competitiveness of the UFP technology. Estimate capital cost and cost of hydrogen and electricity for a UFP plant and compare these costs with IGCC technology costs. A "Go/No Go" decision will be made based on the results of economic feasibility analysis of the UFP technology.
- Quantify and assess the attrition, lifetime and performance of sorbent materials through bench-scale attrition testing and pilot-scale testing.
- Investigate the quality of the third-reactor product stream fed to the gas turbine; characterize the particulate, pollutant and other impurity concentrations in the stream and gauge the need for gas cleanup prior to feeding to the gas turbine.

The current UFP program tasks and schedules are summarized in Table 1-1.

ID	Task Name	2005				2006				2007		
		Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3
1	Task 1 Economic Assessment & System Analysis											
2	Task 2 Attrition Testing (Bench-scale)											
3	Task 3 Pilot Plant Baseline Testing & Contaminant Fractionation											
4	Task 4 Parametric Testing											
5	Task 5 Long Term Testing											
6	Task 6 Kinetic Modeling & Conceptual Prototype Design											
7	Task 7 Management & Reporting											

▲ Go/No-Go decision

Table 1. Main tasks and schedules for Phase II UFP program.

UFP TECHNOLOGY

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. CAM is a sorbent that absorbs CO_2 to form CAM- CO_2 . OTM is a metal oxide, which can be oxidized to form OTM-O. A mixture of the bed materials and coal ash is present in each reactor, and the bed materials undergo a variety of transformations and reactions as they move from one reactor to another. Each reactor serves a different key purpose: gasification, CO_2 release, or oxidation.

The first reactor from the left (R1) is the site of initial coal gasification. Coal fed to R1 is partially gasified with steam, producing H_2 , CO and CO_2 . Conditions in R1 facilitate CO_2 absorption by the CAM ($CAM + CO_2 \rightarrow CAM-CO_2$). The reduction in gas-phase CO_2 concentration shifts the equilibrium of the water-gas shift reaction to deplete CO from the gas phase ($CO + H_2O \rightarrow H_2 + CO_2$). The removal of both CO and CO_2 from R1 results in a H_2 -rich product stream suitable for use in liquefaction, fuel cells, or turbines. The circulation of bed materials provides a continuous supply of fresh CAM from the middle reactor (R2) and transfers spent CAM to R2 for regeneration.

The middle reactor is the location of CO_2 release from spent CAM ($CAM-CO_2 + \text{heat} \rightarrow CAM + CO_2$). The CO_2 sorbent is regenerated as the hot bed material transferred from the third reactor from the left (R3)

Figure 1. Conceptual design of the UFP technology.

enters R2, increasing the bed temperature to the level required for CO₂ release. This CO₂ release generates a CO₂-rich product stream suitable for sequestration. In addition, char present in the bed materials transferred from R1 is completely gasified in R2. The oxidized OTM transferred from R3 is reduced as it provides the oxygen needed to oxidize CO to CO₂ and H₂ to H₂O (OTM-O + CO → 2OTM + CO₂ or OTM-O + H₂ → 2OTM + H₂O).

The OTM is oxidized in R3 (2OTM + ½ O₂ → OTM-O + heat). Air fed to R3 re-oxidizes the OTM via a highly exothermic reaction that consumes most of the oxygen in the air fed. Thus, R3 produces high-temperature, high-pressure oxygen-depleted (vitiating) air for a gas turbine expander as well as generating heat that is transferred to R1 and R2 via solids transfer.

Reactor 2 exchanges bed materials with both R1 and R3 (there is no direct R1-R3 transfer), allowing for the regeneration and recirculation of both the CAM and the OTM. CAM absorbs CO₂ in R2 and releases it in R2. OTM is oxidized in R3 and reduced in R2. 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.

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.

The project team continues to meet regularly to assess progress, distribute workload, and identify and remove potential roadblocks. An expanded 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.

EXPERIMENTAL

ECONOMIC ASSESSMENT

Current work on the UFP technology is aimed at reducing the technical and economic risks associated with a commercial full-scale UFP-based energy plant. Although developments efforts have thus far focused on the fundamental reactions and processes of the UFP, continuing development will also consider and assess issues such as combined cycle plant integration, environmental impact, and long-term control and operability; issues that directly impact the economic and commercialization potential of the proposed process. The process design will be updated and serve as the basis for an assessment of the economic viability of a full-scale UFP-based system.

The economics of the UFP process are an important aspect of development efforts. GE Global Research is working with Worley Parsons to develop detailed estimates of UFP plant costs to assess the commercialization potential of the technology as well as to guide future development efforts.

UFP System Analysis

In order for Worley Parsons to carry out the economic analysis of the UFP technology, the existing pilot-scale UFP system model must be scaled up to commercial size, which includes developing estimates of reactor sizes, construction materials and auxiliary equipment designs. Scale-up and equipment design requires detailed UFP system analysis to provide inputs to the reactor design, fluidization calculations and for Worley Parsons' CAPEX estimates.

Commercial-scale UFP system analysis was performed using Aspen software. Figure 2 shows a simplified process flow diagram developed using Aspen software. This Aspen analysis was

Figure 2. UFP process flow diagram.

scaled up to account for commercial scale power generation using dual 7FA turbines.

UFP Reactor Design and Scale-up Using Fluidization Modeling

The commercial scale UFP reactor system design can be divided into three phases: (1) Fluidization calculations (2) Fluidization regime mapping/reactor type selection and (3) Reactor geometry optimizations. The following design criteria and resources were considered during these three design phases:

- Fluidization conditions and flow regimes
- Engineering estimations and “rule of thumbs”
- Literature and commercial scale application information, and
- Kinetic limitations.

Fluidization Calculations

During detailed fluidization calculations, solid and gas flow rates, operating conditions, and gas-solid compositions were provided based on Aspen UFP system analysis results. For any given fluidized bed geometry—internal diameter, D and aspect ratio, L_{mf}/D —a series of fluidization condition parameters can be calculated including the minimum fluidization velocity u_{mf} and maximum reactor aspect ratio $(L_{mf}/D)_{max}$, bed void fraction, total reactor height, mass of the bed, solid residence time, superficial gas velocity, etc. By iteratively calculating the fluidization conditions for a series of bed dimensions, a fluidization design map was developed for each reactor.

RESULTS AND DISCUSSION

ECONOMIC ASSESSMENT

Fluidization Calculations

Figure 3 shows the fluidization design map calculated for reactor 1. For a given reactor design point on the map, its Y-axis represents the internal diameter, D , and the X-axis represents the reactor aspect ratio, L_{mf}/D . In this fluidization design map, the red contour represents the total length of the reactor, the blue contour represents the solid residence time, and the yellow contour represents the fluidization parameter u/u_{mf} .

As shown in Figure 3, the fluidization design space can be bounded by the slugging flow conditions. The maximum superficial gas velocity to prevent slugging was calculated, which in turn sets a lower bound on the reactor diameter – the Y-axis. Similarly, a maximum aspect ratio, L_{mf}/D , to prevent slugging can be calculated, which sets the boundary for the X-axis.

The fluidization design map provides a visual means of correlating reactor geometry with fluidization conditions. Based on fluidization theories, engineering estimations and rules of thumb, a desired fluidized bed operation region is identified on the Figure 3 fluidization design map that corresponds to a set of feasible solutions in terms of the reactor dimensions.

Figure 3. Fluidization design map for Reactor 1.

Fluidization Regime Mapping/Reactor Type Selection

The reactor types and fluidization regimes are primarily dictated by the solid and gas flow rates and solid residence time required for the chemical reactions. Bench scale experiments and technical literature results indicate that the kinetics for the gasifier (reactor 1) and regenerator (reactor 2) requires residence times much longer than that of the oxidation reactor (reactor 3).

When assuming bubbling fluidized bed for reactor 1 and reactor 2, these residence time requirements can be met fairly well with reasonable reactor size and bed loading. However, due to the nature of reactor 3, a bubbling fluidized bed design for reactor 3 would result in a very large reactor size and an unnecessarily long residence time of solid materials. Instead, a transport reactor design is more suitable for this reactor.

Figure 4 shows a design map comparison for reactor 3 between bubbling bed design and transport bed design. A bubbling bed design requires twice the number of reactor trains as that of the transport bed reactor. Additionally, each fluidized bed reactor would also require the internal diameter to be several times larger than the transport bed.

Figure 4. Reactor type comparison for oxidation reactor.

Through the use of fluidization design maps, it can be concluded that the gasifier and regenerator reactors should both be designed as bubbling fluidized beds while the oxidation reactor should be designed as a transport reactor. The general fluidization flow regime diagram by Kunii and Levenspiel, as shown in Figure 5, was also used to confirm the selected reactor types and benchmark results against other commercial applications.

Reactor Geometry Optimization

The last phase in the scale-up reactor design is to use fluidization theory, engineering estimates and kinetic limitations to identify a feasible fluidization design space and eventually pinpoint the optimal reactor design.

As a rule of thumb, the optimal operation condition for a bubbling fluidized bed requires the u/u_{mf} ratio to be between 2 and 3. As shown in Figure 4, this condition poses an upper bound and a lower bound on the design space for reactor 1, which can then be translated to a maximum and a minimum reactor diameter on the design map.

Preliminary kinetics provides limitations on the residence time, which can be used to further narrow down the design space horizontally. As shown in Figure 4, the bench scale experiments and technical literature provided kinetic information for setting the left and right boundaries using residence time.

Finally, as shown in Figure 4, the region bounded by red dashed lines represents the optimal reactor geometries for reactor 1. Similarly, the optimal reactor design space was identified all other reactors. The mid point in these design spaces was picked for each reactor as the final reactor geometry design for economic analysis purpose.

Fluidization Analysis – Flow Regime Mapping

Figure 5. Fluidization flow regime analysis.

CONCLUSIONS

Significant progress was made in the seventeenth quarter. The commercial-scale UFP reaction system was successfully designed based on the Aspen system analysis results and fluidization calculations.

Fluidization analysis indicates that, assuming all reactors are bubbling beds, the UFP system would require fairly large reactors. Based on the technical literature as well as existing commercial scale applications, such large reactors would incur considerable increase in capital cost and tremendous technical challenges in terms of material and constructions. A more realistic and economic approach is to divide the UFP system into multi-train reactor systems that are within commercially available vessel sizes of similar applications.

Furthermore, according to different gas-solid flow rates, reactor 1 and 2 are designed as bubbling fluidized bed while reactor 3 is designed as a transport reactor. The sizes and fluidization conditions of each reactor are also calculated. These reactor designs provide the quantitative basis for the economic analysis of the UFP system viability.

FUTURE WORK

Further validation and engineering analysis, including particle size distribution analysis, are planned to aid in finalizing the existing reactor designs. Other peripheral equipments for the UFP system, i.e. refractory, reactor vessel shell, solid transfer ducts, cyclone, etc. will also be designed or estimated.

In the next quarter, a list of equipment and specifications for the UFP reaction system will be generated for use in the preliminary economic analysis of the UFP technology. Information on the IGCC case and Polygen-IGCC case will also be provided to Worley Parsons so that they can provide estimates on the economics of alternative IGCC-based technologies for comparison with the UFP results.

Other future work on UFP technology development will include attrition testing of sorbent lifetimes in the bench-scale experimental system. Additional experimental testing of the UFP process at pilot scale will also be conducted after the system is upgraded based on lessons learned from previous experimental efforts.

The continuing analysis of UFP economics based on experimental and modeling results will provide the data necessary to identify areas that have the most significant impact on the UFP's commercialization potential. These tasks will aid in ensuring that the UFP system will meet the needs of the power generation industry both efficiently and economically.

REFERENCES

Kunii, Daizo and Levenspiel, Octave, Fluidization Engineering 2nd Edition, Butterworth-Heinemann, 1991. (pp 48-50, 359-365)

LIST OF ACRONYMS AND ABBREVIATIONS

CAM	CO ₂ Absorber Material
CTQ	Critical to Quality
DFSS	Design for Six Sigma
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
UFP	Unmixed Fuel Processor
U.S. DOE	United States Department of Energy