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

Phase II

Quarterly Technical Progress Report No. 18

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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 is developing 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 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 April 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 CO_2, 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 CO_2 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 CO_2 and pollutants from the vent gas, while simultaneously maximizing coal conversion efficiency and hydrogen production. The Phase I effort integrated experimental testing, modeling and preliminary 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 polygen 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 eighteenth 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 July 01, 2005 and ending September 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 eighteenth 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 second 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 July 01, 2005 and ending September 30, 2005. The report provides a description of the technology concept and a summary of program activities and accomplishments.

During the third quarter of 2005, the work on addressing the economic feasibility risk (Task-1) was continued. Scale-up tools were developed for the conceptual design of an UFP-based full-scale system combined with a power island. Aspen software was used to develop material and energy balances 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. The scale-up information was provided to Worley Parsons to carry out an independent assessment of the cost of UFP technology. Worley Parsons reviewed the UFP information and provided the capital cost estimates for a full scale UFP process combined with a power island. Worley Parsons also provided capital cost estimates for IGCC and IGCC polygen system with CO_2 separation. Based on the capital cost and material and energy balance provided by Worley Parsons, cost of hydrogen and electricity were calculated for the UFP and IGCC technologies. Currently GE is reviewing this “apples-to-apples” cost comparison information internally. The methodology for obtaining this information is described in the current quarterly report.

The risk of sorbent attrition and lifetime (Task-2) has also been addressed in the last quarter. The design of the bench-scale fluidized bed facility (from the Phase I effort) has been revisited and the system was upgraded to conduct physical attrition tests of various sorbents. Detailed P&ID drawings have been developed and upgraded systems are being procured. Some physical attrition tests were performed by standard ASTM tests by Research Triangle Institute (RTI) for comparison basis.

A separate set up for the chemical attrition evaluation has been assembled at the materials characterization lab of GE Global Research in Niskayuna, NY. Tests are currently being conducted using this set up to characterize targeted sorbents for this technology through cycling and analyzing solid material samples using precision instrumentation.

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 CO_2. 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.

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.

Task #	Task Name	2005				2006				2007			
		Qtr1	Qtr2	Qtr3	Qtr4	Qtr1	Qtr2	Qtr3	Qtr4	Qtr1	Qtr2	Qtr3	Qtr
1	Task 1: Economic Assessment & System Analysis												
2	Go/No Go Decision Based on Economics												
3	Task 2: Attrition Testing (Bench-scale)												
4	Task 3: Pilot Plant Baseline Testing & Contaminant Fractionation												
5	Task 4: Parametric Testing												
6	Task 5: Long Term Testing												
7	Task 6: Kinetic Modeling & Conceptual Prototype Design												
8	Task 7: Management & Reporting												
9	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 + heat $\rightarrow$ CAM + CO_2). The CO_2 sorbent is regenerated as the hot bed material

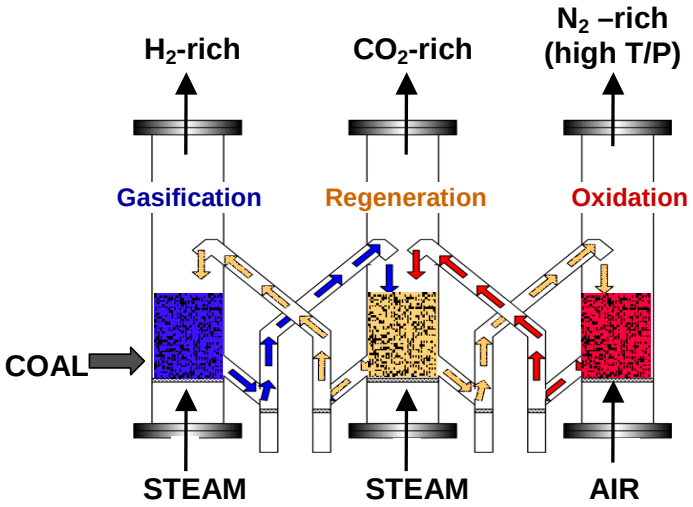

Figure 1 Conceptual design of the UFP technology

transferred from the third reactor from the left (R3) enters R2, increasing the bed temperature to the level required for CO_2 release. This CO_2 release generates a CO_2-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 CO_2 and H_2 to H_2O (OTM-O + CO $\rightarrow$ 2OTM + CO_2 *or* OTM-O + H_2 $\rightarrow$ 2OTM + H_2O).

The OTM is oxidized in R3 (2OTM + ½ O_2 $\rightarrow$ 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 (vitiated) 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 CO_2 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 technology. The process design will be updated and serve as the basis for an assessment of the economic viability of a full-scale UFP-based plant.

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 and guide future development efforts.

The economic analysis consists of the following tasks:

- Scale-up analysis of an UFP-based Polygen process to commercial scale using Aspen/Gate-cycle software.
- Preliminary design of commercial size reactors and auxiliary unit operations for CAPEX estimate.
- CAPEX and O&M cost estimates for UFP & IGCC polygen technologies.
- Calculation of cost of electricity and cost of hydrogen.

Scale-up tools were developed for the conceptual design of an UFP-based full-scale system combined with power-island. Aspen software was used to develop material and energy balances 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. The scale-up information was provided to Worley Parsons to carry out an independent assessment of cost of UFP technology. Worley Parsons reviewed the UFP information and provided the capital cost estimates for a full scale UFP process combined with a power-island. Worley Parsons also provided capital cost estimates for IGCC and IGCC polygen system with CO_2 separation. Based on the capital cost and material and energy balance provided by Worley Parsons, cost of hydrogen and electricity were calculated for the UFP and IGCC technologies. Currently GE is reviewing this “apples-to-apples” cost comparison information internally.

Scale-up of UFP Process: Reactor Design Optimizations

During this quarter, the scale-up calculation was focused on optimizing the reactor designs of the commercial scale UFP process for the economic analysis. Sensitivity analysis was performed for the geometry of each of the three reactors as a function of the particle size of the CAM & OTM material. These calculations and analysis provided crucial information for the optimization of reactor designs to achieve the desirable fluidization conditions as well as the optimal solid separation approaches.

Peripheral Equipment Cost Estimations

Based on the optimal reactor geometries for the UFP system, the following equipments were also designed and their cost was estimated:

1. Refractory materials for each reactor
2. Reactor metal shell material.
3. Solid transfer legs
4. Cyclones and filtration units

The list of equipment specifications along with the UFP process flow diagram were completed and submitted to Worley Parsons.

Capital Cost Estimation & Systems Analysis by Worley Parsons

Worley parsons carried out systems analysis for a conventional IGCC process, IGCC polygen system with CO_2 capture and the UFP process. Worley Parsons used GateCycle software for power-island analysis. GE simulated the chemical processes using Aspen Plus. Worley Parsons estimated the capital cost for the above technologies using their cost database for the IGCC processes and also the scale-up information about the UFP technology provided by GE.

Cost of Hydrogen and Eletricity estimation

GE calculated the costs of hydrogen and electricity using an economic analysis model based on DOE's H2A model. The cost results are being reviewed internally by GE Global Research and GE Energy.

Attrition Testing and Solids Lifetime Assessment

Task 2 of the current phase started was initiated at the end of the current quarter. The objective of this task is two-fold:

1. Evaluate solids (CAM & OTM material) attrition and extrapolate results to a commercial size plant
2. Evaluate lifetime of solids to obtain deactivation profiles as a function of number of cycles.

RESULTS AND DISCUSSION

ECONOMIC ASSESSMENT

Reactor Scale-up for Capital Cost estimate

The size of the UFP reactors for a commercial scale plant was estimated. The scale-up was performed in such way that the UFP process can be integrated with two 7-FA gas turbine expanders.

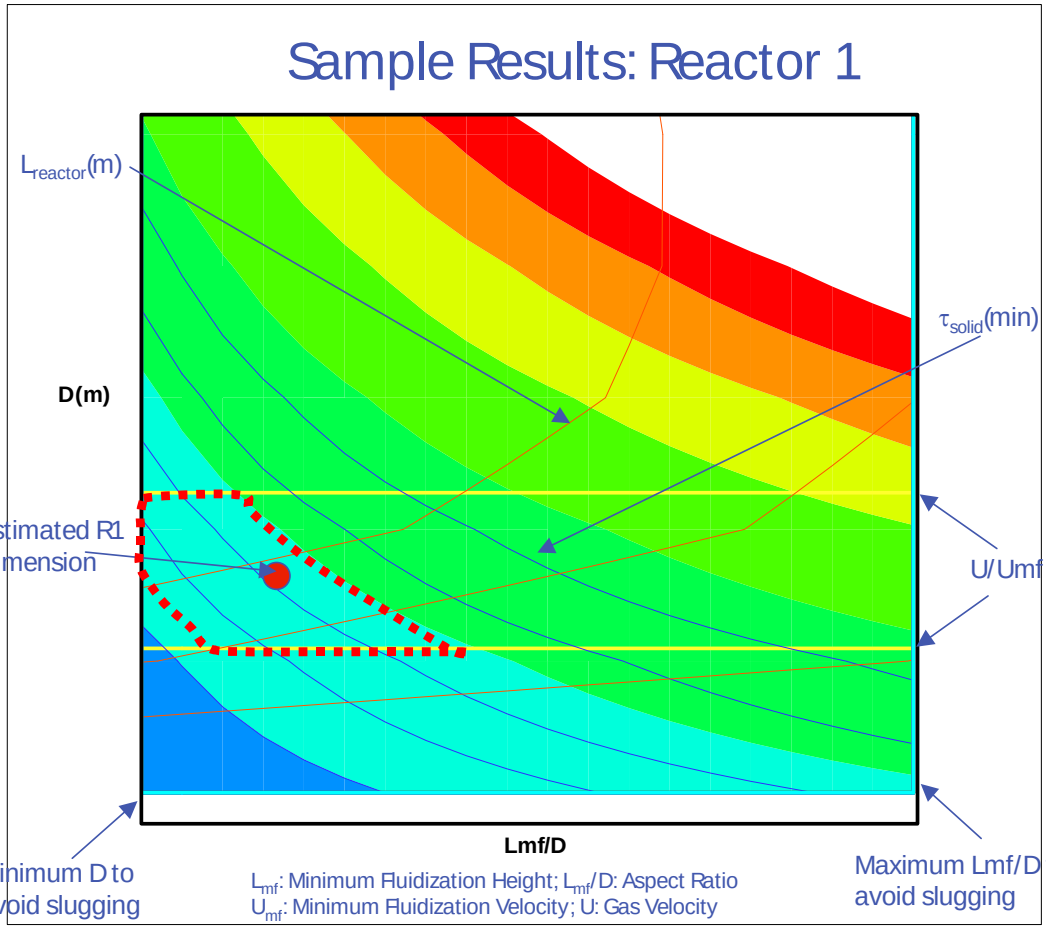

Figure 2 Fluidization design map for Reactor 1

Detailed fluidization calculations were conducted over the last quarter based on Aspen system analysis results. For any given fluidized bed geometry (internal diameter D and aspect ratio Lmf/D), important data characterizing the fluidization conditions was 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 over a series of reactor geometries, a fluidization design map was developed for each reactor, as shown in Figure 2.

Further fluidization calculation was carried out to study the effect of particle sizes of the CAM & OTM material on reactor geometries. Generally, smaller particles require lower fluidization gas velocity and higher transport disengagement height to prevent particle entrainment.

Figure 3 shows various particle sizes of solids in reactor 1 and their corresponding reactor lengths that are required to prevent particles from being conveyed out of the fluidized bed. As the particle size decreases, the required transport disengagement height increases, resulting in an increase in the total reactor height. After a critical height of reactor, the decrease in particle size would result in much faster increase in the total reactor height required and thus a significant increase in the capital cost of the reactor vessel. At this point, the height of the reactor will only allow particles smaller than the critical particle size to escape from the reactor, which can then be collected using a cyclone and re-injected back to the reactor. Therefore, the critical reactor length was chosen as optimal design point.

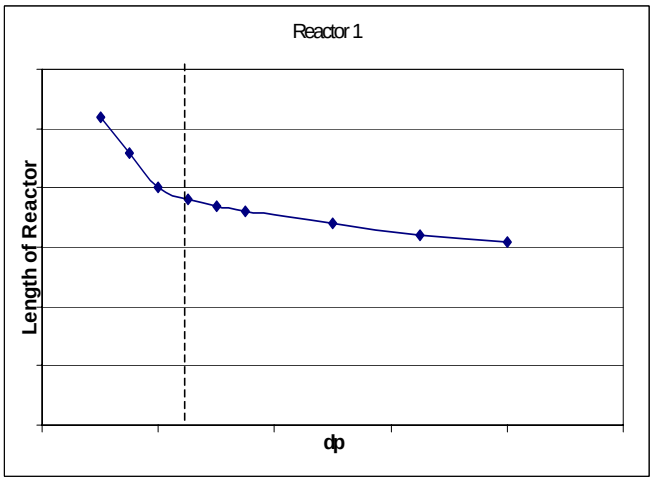

Figure 3 Reactor length required for different particle sizes

Auxiliary Equipment Cost Estimations

Once the reactor dimensions were finalized, detailed designs & cost estimations for the auxiliary equipment were carried out including refractory, reactor vessels, solid transfer ducts and solid separation equipments.

Typical refractory and metal shell materials were selected for the UFP reactors. Pressure vessel shell thickness and reactor heat transfer (Figure 4) calculations were performed for each reactor to determine the thickness of each layer of materials to satisfy both the temperature and the pressure requirement of the reactors according to the ASME codes.

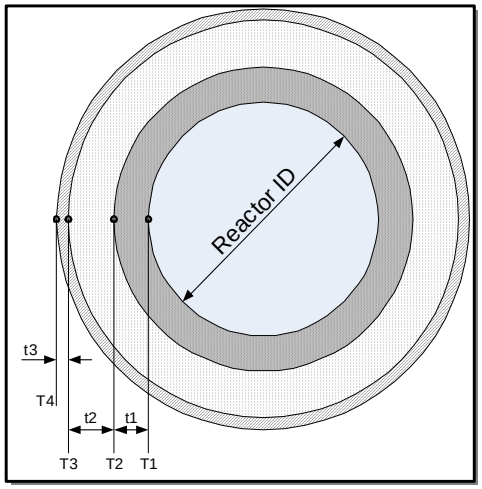

Figure 4 Refractory and shell thickness estimation

Designs for solid transfer ducts were also estimated. According to the different temperature and pressure requirements for each solid transfer ducts, their corresponding refractory and shell materials and thicknesses were also estimated.

Fluidization calculation results were used when determining the solid separation equipments for the UFP processes. Gas and entrained solid flow rates were sent to outside vendors of gas/solid separation units for estimation of cyclone sizes and costs. Based on the vendor feedback, it is determined that one cyclone per reactor is sufficient for reactor 1 and reactor 2. Three to four cyclones would be required for reactor 3 due to its high solid flow rate. Final costs were estimated based on these configurations and unit cost estimations provided by outside vendors. Worley Parsons used this information for the final economic analysis of the UFP technology.

Cost of Hydrogen and Electricity Estimate

The economic viability of the proposed UFP process for producing hydrogen depends on recovering process energy as electricity. The electricity is sold to add to the positive cash flow in the overall plant economic analysis. The DOE H_2A Excel model for calculating the required selling price of hydrogen accommodates this as "by-product Electricity" and allows the entry of a selling price of electricity. Since the value of the electricity and hydrogen streams are of the same order of magnitude, the selection of the selling price of electricity is extremely important in determining the price of hydrogen. The following describes an approach that uses the H_2A model to first calculate a selling price of electricity for an electricity only plant and then uses this value to calculate the selling price of hydrogen for hydrogen and electricity plant.

The integration of the UFP process into power generation plant can be viewed as similar to replacing the gasification process in an Integrated Gasification Combined Cycle (IGCC) plant that has been modified to produce hydrogen from a portion of the syngas product. In order to obtain a set of consistent set of equipment cost numbers Worley Parsons was contracted to calculate Total Installed Equipment costs and performance estimates for three main plant configurations.

The first configuration, Case 1, is for a typical GE Texaco IGCC quench system that produces only electricity. Case 2 is for a system where the coal handling and gasification streams have been increased in capacity to allow a portion the syngas stream to be diverted to a shift reactor to produce hydrogen. In Case 3 the gasifiers are replaced with the UFP process and the power generation equipment is modified to accept the hot exhaust stream. Since one of the attributes of the UFP process is the presence of a CO_2 rich stream, which is favorable for CO_2 separation, Cases 2s and 3s were analyzed which include equipment to separate and compress CO_2 .

The Inputs to H_2A model were adjusted for Case 1 for a hypothetical H_2 production plant with a capacity 1 kg/day. Using 1 kg/day, the inputs for coal feed rate and by-product electricity, which are entered per unit of H_2 production, are simply the plant daily capacities. By then, entering a very small value for the required selling price of hydrogen on the H_2A Cash flow Analysis sheet ($1e-7 was used), the selling price of electricity can be adjusted so that the Net Present Value of the cash flow streams is zero. This is the same approach that is normally used to generate the Required Selling Price of hydrogen. This selling price of electricity, calculated for Case 1, is then used, along with same financial assumptions, to calculate a cost of hydrogen for the other equipment configuration cases.

The results of economic analysis are currently being reviewed by GE GRC and GE Energy.

Sorbent Attrition and Lifetime Assessment

Physical Attrition

The three main sources of physical attrition of CAM & OTM can be categorized in:

- High velocity impact, which is generally caused by high velocity jets within the fluidized bed causing particle entrainment.
- Low velocity impact, which is caused by particle-to-particle contact and within a bubble media. The fluidization linear velocity and the mass of the bed itself are the main contributors for this category.
- Particle-wall impacts: These become negligible at large scale commercial reactors. The critical factor is the ratio of the mean particle size to the reactor diameter ($d_p/D_{reactor}$).
- Other sources: auxiliary units or components in the fluidized bed processing plant also create additional attrition. Examples are attrition inside cyclone units, and attrition in riser and solids return legs in circulating fluidized bed designs.

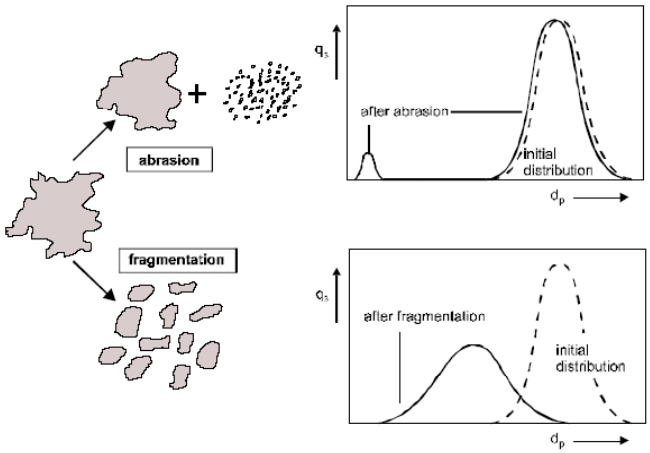

Figure 5 Particle distribution as result of attrition

Regardless of the kind of source, attrition typically results in two basic categories of particle distribution: by abrasion and/or by fragmentation. From abrasion, very fine particles are created; and from fragmentation, individual particles are typically larger. These two types will generate narrow and wide particle size distributions, respectively, as illustrated figure 5. Methods of evaluating attrition are scarce and mostly empirical. In the case of fluidized beds, the attrition testing techniques typically do not account for attrition within the bed, i.e., particles resulting from attrition that remain in the bed. Attrition levels are measured in respect to the particles that leave the bed by entrainment.

There are industry-accepted standard methods to evaluate attrition levels. The catalyst industry primarily utilizes ASTM D-5757 (1995 and 2000) for evaluating samples for attrition properties (equipment in the figure next). Research Triangle Institute (RTI) performed these tests for various CAM & OTM materials. These test employ a bed fluidized by air jet to create inter-particle collisions. The response of such test is given in terms of material weight loss during at 1 and a 5 h test period. The limitation of this apparatus is that it uses standard conditions of flow, temperature and pressure, and therefore, it is suitable for material screening only. It will not determined attrition level at specific fluidized bed absolute conditions, although it will determine attrition relative to two or more different materials, which in turn can be used to estimate attrition at the process condition.

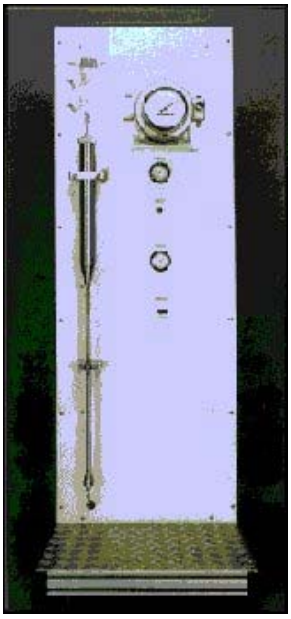

Figure 6 ASTM D757 apparatus

The objective of the physical attrition task is to determine particle attrition levels at the commercial scale operation. Several solid CAM & OTM materials of interest were obtained as summarized in Table 2.

	Material	Description
1	Material 1	CO_2 sorbent
2	Material 2	CO_2 sorbent
3	Material 3	CO_2 sorbent
4	Material 4	Oxygen-transfer material
5	Material 5	Oxygen-transfer material

Table 2 Examples of CO_2 sorbent and oxygen transfer materials.

A methodology has been developed to estimate the physical attrition of sorbents used in UFP process. This method encompasses a combination of ASTM attrition measurements and fluidized bed bench-scale testing. It is illustrated in Figure 7.

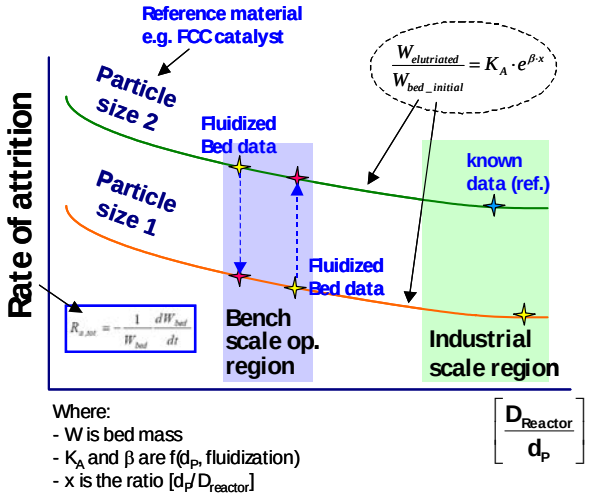

Figure 7 Illustration of the method to evaluate physical attrition and extrapolate to commercial scale operation

With this test, data can be obtained on relative physical attrition comparing the materials in question and a standard characterized material, in this case a FCC catalyst. The attrition index (AI) is calculated from:

$$\frac{WeightLoss\%_{5-hour} - WeightLoss\%_{1-hour}}{4}.$$

Once AI is known for each one of the candidate materials listed above, the relative AI is determined. This is the ratio between the AI of the material (particle 1 in the plot) over the AI of the standard reference (particle 2). Upon testing each material, including the standard in the fluidized bed bench-scale, one data point in the plot will be determined (yellow stars), which named FBAI (fluidized bed attrition index). Because it is impractical to change the diameter of the fluidized bed reactor, only one experimental point can be obtained for each particle. The concept of the relative AI will be used to determine a 2nd data point for each particle curve, by multiplying the FBAI by the relative AI, for instance:

$$FBAI_{particle-2} \times \left(\frac{AI_{particle-1}}{AI_{particle-2}} \right)_{ASTM-data} \Rightarrow FBAI_{particle-1}$$

Where $FBAI_{particle-2}$ is the yellow start data-point on the particle 2 curve and $FBAI_{particle-1}$ is red star data-point on the particle 1 curve, both taken at the same ratio $D_{reactor}$-to-d_p from figure 7. The $FBAI_{particle-2}$ in this case is a calculated point at constant $D_{reactor}$-to-d_p. This methodology assumes that:

a. The relative attrition ratio between particles remains a constant, independent of the nature of the particle; and
b. The attrition decay curves are parallel to each other, and asymptotic.

These two assumptions are reasonable according to the literature reviewed. These assumptions will be further verified when the data-points are plotted. The level of attrition at a commercial scale system is determined at the point of the asymptote. For the reference material, since the attrition levels are known at industrial scale, it will be used to validate the methodology. This flow down chart illustrates the method to extrapolate attrition levels to industrial scale, including validation.

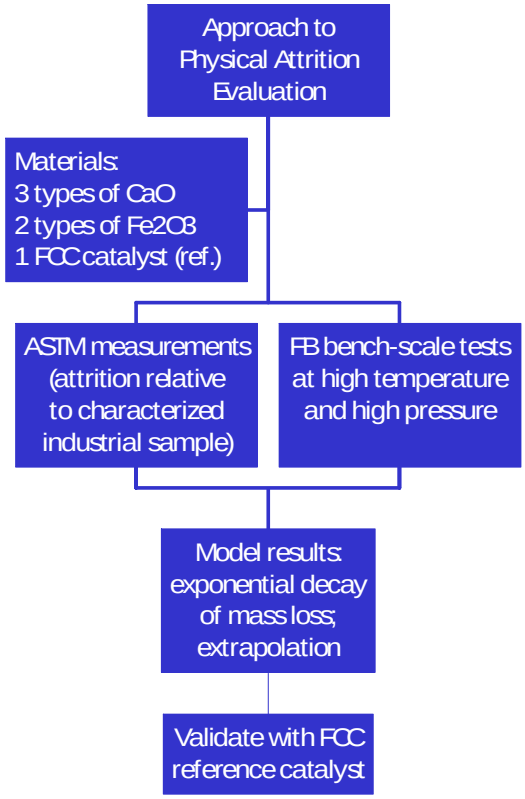

Figure 8 Approach to evaluate physical attrition

Below are results of the AIs from ASTM measurements and the mean particle size performed at RTI.

Materials	Average particle size (microns)	Attrition Index (%loss per hour in ASTM test
FCC catalyst (for reference)	70	0.62
Material 1	241	0.69
Material 2	270	2.72
Material 3	593	2.37
Material 4	224	3.94
Material 5	334	1.71

Table 3 Physical attrition measurement results (materials correspond to list in table 2)

The average particle size of the standard material is typically 65-70 micron where as those of the candidate materials are considerably larger. With that in mind, is it reasonable to conclude that:

a. Material 1 is significantly more attrition resistant than material 2
b. Materials 1 has strong attrition resistance, potentially as good as the reference material
c. Material 4, with mean particle size ~200 μm, is probably less attrition resistant than material 5, with mean particle size ~300 μm.

Again, it is important to clarify that these AIs are useful for comparison only, and cannot be extrapolated to attrition level at several hours under operation (>> 5 h). This is the purpose of the methodology, as described here. Another remark on the ASTM results is that one does not know the extent of particle size effect on the results at this point. Generally attrition increases with the square of particle size. However, it is unclear whether this generalization applies to different materials. Assuming this assumption is true, all candidate materials seem to be attrition resistant in comparison to standards. For true comparison, targeted materials should be first made in the size range of 65-70 μm and then retested. Experiments are planned to validate this hypothesis.

The bench-scale fluidized bed system assembly progressed to the point that approx. 60% of the work has been completed. Figure 9 shows the P&ID of the unit.

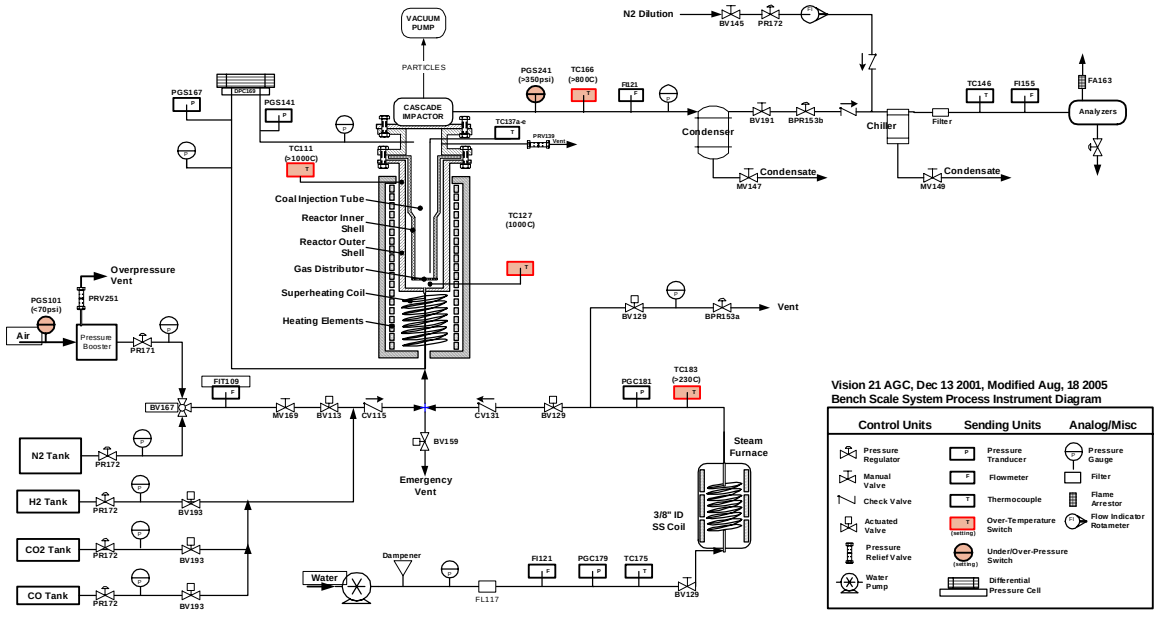

Figure 9 P&ID of bench scale system for measurement of physical attrition

Chemical Attrition

Task 1:

In this task, we are developing testing protocol whereby the attrition of the CAM & OTM particle sorbents resulting from chemical cycling can be studied. A furnace apparatus has been constructed where attrition due to chemical reactions can be characterized. A schematic of the apparatus is shown in Figure 10. The apparatus can be used to investigate the CAM as well as the OTM. Nitrogen is fed into mass flow meter MFM1. Input gas (oxygen or CO_2) is fed through mass flow controller MFC1. The gas mixture (oxygen or CO_2 + N_2) is fed into the furnace. In the absence of absorption or desorption, the gas flow through the outlet (MFC2) equals the sum of MFM1 and MFC1. If gas is being adsorbed, additional nitrogen is drawn from MFM1 to compensate gas flows. If gas is being desorbed, the flow from MFM1 is diminished. The respective flows are monitored via computer interface. Consequently, a plot of dm/dt vs t is a measure of adsorption or desorption events. Experimentation using commercial CAM and OTM sources is under way.

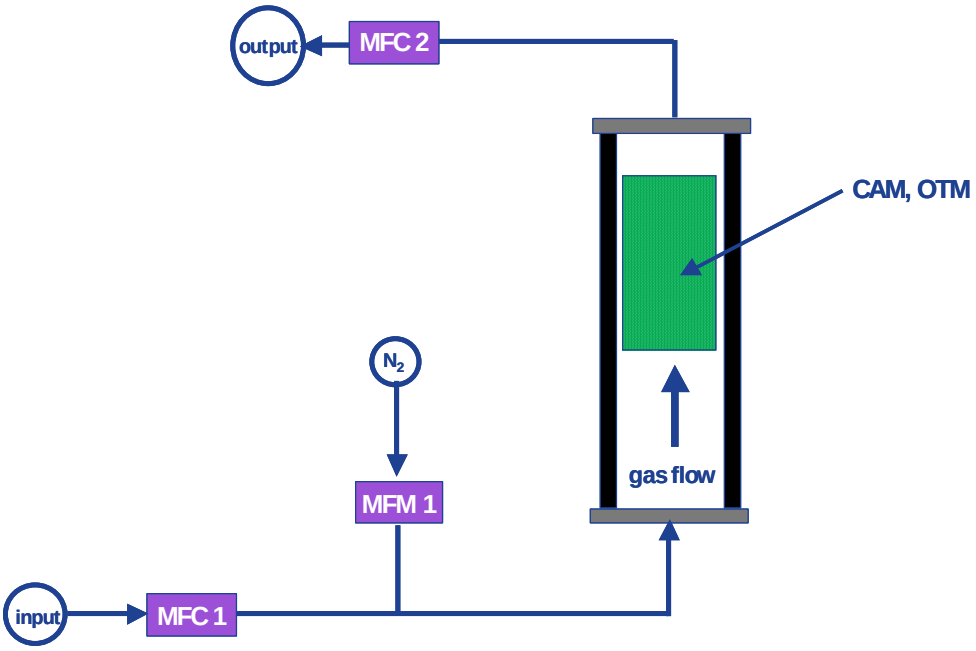

Figure 10 Schematic of chemical attrition apparatus

The anticipated output from these experiments is two-fold. First, degradation of the absorption/desorption properties can be monitored over multiple cycles. Second, XRD, SEM, BET, etc can be used to analyze changes in particle morphology.

Task 2:

Reactivity between the various chemical species is of considerable risk. Consequently, thermodynamic studies are underway which will offer insight into the potential reactivity of the sorbents, furnace lining, coal slag, etc. Note that these analyses are entirely thermodynamic in nature; these reactions may be kinetically limited depending on the nature of the interaction. Nonetheless, an understanding of the nature of these interactions is important to gaining a better understanding of materials interactions.

TDATA© version 4.74 was used to analyze the equilibrium composition of R1 in the 3-reactor UMC design. Of note is the fact that considerable reactivity between the OTM and CAM is predicted. The ramifications are two-fold. First, the CO_2 capture efficiency may be reduced significantly if a CAM-OTM complex is formed. Second, The dry mass percent hydrogen collected in R1 is diminished (85% vs. 90%+) due to CO_2 slip. Similar analyses based on R2 and R3 are currently under way.

CONCLUSIONS

During this quarter, effects of particle size distribution on the reactor design were carefully studied and the optimal reactor dimensions were identified. Reactor vessel, refractory and solid transfer ducts were designed based on the optimized reactor geometries. Solid separation equipments were also identified and their costs estimated. The final commercial-scale UFP reaction system design and process specifications were compiled into a detailed equipment list along with UFP process flow diagram. This equipment list was submitted to Worley Parsons for economic analysis. Worley Parsons estimated the capital cost of the UFP process. Cost of hydrogen and electricity were calculated based on this capital cost and the systems analysis results. The results are currently being reviewed internally by GE.

Attrition testing and solid lifetime (bench scale), which is Task 2 of the current phase of the program, was also initiated during this quarter. Preliminary bench-scale equipments were identified. Experiments to determine the physical and chemical attrition of the CAM and OTM materials are in progress.

FUTURE WORK

Attrition testing and sorbent lifetime assessments in the bench-scale experimental system will be the focus of the next quarter. 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. Upgrades in the pilot scale system will be also initiated in the next quarter.

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.

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