Zero Emissions Coal Syngas Oxygen Turbo Machinery

Final Scientific/Technical Report

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ABSTRACT

Siemens Energy, Inc. (formerly Siemens Westinghouse Power Corporation) worked with Clean Energy Systems and Florida Turbine Technologies to demonstrate the commercial feasibility of advanced turbines for oxy-fuel based power systems that discharge negligible CO₂ into the atmosphere. The approach builds upon ultra supercritical steam turbine and advanced gas turbine technology with the goal of attaining plant efficiencies above 50% in the 2015 timeframe.

Conceptual designs were developed for baseline, near term, and long term oxy-fuel turbine cycles, representing commercial introductions of increasingly advanced thermal conditions and increasing exposure to steam-CO₂ mixtures.

An economic analysis and market demand study was performed by Science Applications International Corp. (SAIC), and indicated that long-term oxy-fuel turbine cycles start to look attractive in 2025 when the CO₂ tax is assumed to reach \$40/ ton, and by 2030 it has a clear advantage over both IGCC with sequestration and pulverized coal with sequestration. A separate risk analysis of the oxy-fuel combustor, HP turbine, re-heater, and IP turbine of the long-term cycle identified and categorized risks and proposed mitigation measures.

In 2007 the program began to focus on a potential oxy-fuel turbine power generation demonstration project in the 2012 -13 time period while still maintaining a link to the requirements of the long-term oxy-syngas cycle. The SGT-900 turbine was identified as the best fit for modification into an intermediate pressure turbine (IPT) for this application.

The base metals, bond coats, thermal barrier coatings (TBCs), and rotor materials used in the SGT-900 were tested for their ability to operate in the steam- CO₂ environment of the oxy-fuel OFT-900. Test results indicated that these same materials would operate satisfactorily, and the plan, is to use SGT-900 materials for the OFT-900.

Follow-on programs for corrosion testing and evaluation of crack growth rates in oxy-fuel environments have been proposed to build on these results and provide quantifiable assessments of the effects of oxy-fuel environments on the service lives of turbine components.

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1.0 EXECUTIVE SUMMARY

Siemens Energy, Inc. (formerly Siemens Westinghouse Power Corporation), with support from Clean Energy Systems and Florida Turbine Technologies, worked to demonstrate the commercial feasibility of an advanced turbine for oxy-fuel based power systems that discharge negligible CO₂ into the atmosphere. The approach builds upon ultra supercritical steam turbine and advanced gas turbine technology and makes logical step advancements to attain plant efficiencies above 50% in the 2015 timeframe.

Conceptual designs were developed for baseline, near term, and long term oxy-fuel turbine cycles.

- The baseline cycle is an 'indirect' cycle based on 2006-level technology whereby the oxy-fuel combustor provides heat for a Heat Recovery Steam Generator (HRSG) with a secondary loop of steam, which provides main and reheat steam to the HP and IP turbines at currently achievable temperatures. Materials of construction would be the same as those used in the current line of Siemens steam turbines.
- The near term cycle and turbines feature higher inlet temperatures for the HP and IP turbines, representing designs that would be commercially available about five years in the future. Materials of construction would be modified for presence of CO₂ and H₂O.
- The long term cycle and turbines are designed for maximum cycle efficiency resulting from even higher HP and IP turbine inlet temperatures. Materials development would be more ambitious than for the 'near term' turbine, with break-through advances expected in Thermal Barrier Coatings (TBCs), cooling technologies, ceramics, powder metallurgy and other areas. Materials of construction would be modified for presence of CO₂ and H₂O at elevated temperatures.

The three cycles show a progression of increasing exposure to steam-CO₂ mixtures and increasingly high temperatures.

Economic and risk analyses were performed on conceptual designs of the long-term cycle. The economic analysis and market demand study was performed by Science Applications International Corp. (SAIC), and indicated that oxy-fuel turbine cycles start to look attractive in 2025 when the CO₂ tax is assumed to reach \$40/ ton, and by 2030 it has a clear advantage over both IGCC with sequestration and pulverized coal with sequestration. The risk analysis of the oxy-fuel combustor, HP turbine, re-heater, and IP turbine of the long-term cycle identified and categorized risks and proposed mitigation measures.

Due to funding limitations starting in 2007, the program took a nearer term perspective intended to closely support a potential oxy-fuel turbine power generation demonstration project in the 2012 -13 time period while still maintaining a link to the requirements of the long-term oxy-syngas cycle. The SGT-900 turbine was identified as the best fit for modification into an intermediate pressure turbine (IPT) for this application, and its materials were evaluated for their suitability to oxy-fuel service.

An initial concern was the potential formation of carbonic acid ($\text{CO}_2 + \text{H}_2\text{O} \rightleftharpoons \text{H}_2\text{CO}_3$), but chemical equilibrium analyses of the drive gas showed that turbine operating conditions virtually precluded the formation of carbonic acid within the turbine.

The remaining concerns associated with the steam/CO₂ drive gas are due to its high H₂O content, which affects the formation of protective oxides on turbine materials, specifically the nickel and cobalt base superalloys used in blades and vanes.

The base metals, bond coats, thermal barrier coatings (TBCs), and rotor materials used in the SGT-900 were tested for their ability to operate in the steam- CO₂ environment of the oxy-fuel OFT-900. Test results indicated that these same materials would operate satisfactorily, although with slightly reduced service lives. The plan for the OFT-900, therefore, is to use the same materials that were used in the SGT-900.

Follow-on programs for corrosion testing to 3,000 hours in oxy-fuel environment and evaluation of the crack growth rate of Blade 1 and 2 alloy IN738 in environment have been proposed. These follow-on programs will build on the results presented here and provide a more conclusive and quantifiable assessments of the effects of oxy-fuel environments on the service lives of turbine components.

2.0 PROGRAM OVERVIEW

Oxy-fuel combustion provides a conceptually simple way to remove CO₂ from a fossil-fueled power plant. In these systems, hydrocarbon fuel is burned with nearly pure oxygen and evaporating feedwater to produce a working fluid comprising mostly steam and CO₂. The working fluid produces power in advanced expansion turbines, after which its water component is condensed, leaving the CO₂ to be compressed and stored or utilized. The use of oxygen instead of air removes nitrogen from the combustion process, virtually eliminating NO_x emissions.

Power generation using oxy-fuel combustion has been demonstrated on a small scale by Clean Energy Systems (CES), Inc of Rancho Cordova, California. Making these oxy-fuel cycles competitively efficient requires advanced steam-like turbines operating at gas-turbine temperatures, which turbines have not been developed. The turbine technology development program described here is driven by the potential for highly efficient, utility-scale coal-based power generation without NO_x emissions and with almost 100% capture of CO₂.

Siemens Energy, Inc. (formerly Siemens Westinghouse Power Corporation), with support from Clean Energy Systems and Florida Turbine Technologies, worked to demonstrate the commercial feasibility of an advanced turbine for oxy-fuel based power systems that discharge negligible CO₂ into the atmosphere. The approach builds upon ultra supercritical steam turbine and advanced gas turbine technology and makes logical step advancements to attain plant efficiencies above 50% in the 2015 timeframe.

The overall demonstration program is divided into three phases. Phase 1 explored potential cycles of varying risk, quantifying their efficiencies, costs, and feasibilities in order to confirm that the advanced concept is the logical development goal. Phase 2 includes detailed design, sub-component testing, component testing, and materials testing, as well as the process development required to support the component development. Phase 3 involves the manufacture and prototype testing of system components, including specialized components such as rotating blades and other stationary components critical to the overall performance of the power plant.

This report describes the activities and results achieved under Phase 1 only. Under the current cooperative agreement, the program will not progress to Phases 2 and 3.

2.1 Program Plans

Siemens originally proposed a 9-year, 3-phase Zero Emission Oxy-fuel Turbine program, including turbine design, manufacture, and testing. Phase 1 of this program would last two years and accomplish five tasks:

- Task 1.1 – Cycle Optimization;
- Task 1.2 – Conceptual Design of Turbomachinery and Auxiliary Systems;
- Task 1.3 – Cost and Feasibility Studies;
- Task 1.4 – Research and development Implementation Plan (RDI Plan);
- Task 1.5 – Program Management and Reporting

This program involved a partnership with CES who is responsible for plant cycle modeling and optimizing the fluid conditions to maximize the cycle efficiency. The Siemens turbine development objectives for Phase 1 were as follows:

- Working with CES, define the baseline, near term and far term temperature and pressure conditions for turbines in order to maximize the cycle efficiencies for each time frame. This will lead to cycle selection. Detailed turbine design for the selected cycle would follow in Phase II.
- Develop conceptual designs of turbines suitable for the three cycles (baseline, near and far term) up to a point where risk analysis can be performed to solidify future approach to detailed design that will minimize the technical risks.
- Review of available materials and processes to meet the design needs. Prepare a realistic assessment and a plan to bridge the gap between available materials and those needed to manufacture the turbines as designed.
- Perform cost estimates and feasibility studies. These would be used in economic analysis and risk analysis.
- Develop methods and tools in areas that are most challenging due to their departure from the state-of-the-art technology of gas and steam turbines.

Phase 1 deliverables to DOE-NETL, not including financial reporting, were a Research & Development Implementation Plan, quarterly progress reports, and a final report on Phase 1 effort.

2.2 Program Adjustments

Work during the first two years of the contract focused on cycle optimization, conceptual turbomachinery design, risk analyses, and estimated economics and market demand. Those efforts were concluded in 2007 and reviewed in the 2007 Peer Review.

Funding limitations starting in 2007 caused the focus and objective of the original project to be changed. Starting in FY08, the program took a nearer term perspective intended to closely support a potential oxy-fuel turbine power generation demonstration project in the 2012 -13 time period while still maintaining a link to the requirements of the far-term oxy-syngas cycle. The SGT-900 turbine was identified by Siemens as the best fit for modification into an intermediate pressure turbine (IPT) for this application. A more detailed description of the realigned program is contained in the 2008 White Paper that is included as Appendix I.

The same funding limitations also required the program to proceed at a more moderate pace, and three no-cost extensions were granted that postponed the end date for Phase 1 from September 2007 to December 2009.

Two other activities not in the original scope were added to the program during FY 2008. The first was a plant performance simulation of natural gas and IGCC oxy-fuel cycles conducted by the University of California, Irvine. This study is described in Section 4. The second added activity was a test of turbine materials exposed to actual oxy-fuel products of combustion from the 100-mm (4-inch) CES gas generator at the Kimberlina site in California. This test is described in Section 6.

The remainder of this report describes the main activities and results during Phase 1.

- Research and Development Implementation Plan (Section 3)

- Cycle Optimization (Section 4)
- Conceptual Design of Equipment (Section 5)
- Materials and Coating Evaluations (Section 6)
- Cost and Feasibility Studies (Section 7)
- Risk Assessment (Section 8)

3.0 RESEARCH AND DEVELOPMENT IMPLEMENTATION PLAN

The Research and Development Implementation (RDI) plan was developed during the first six months of the project and submitted to DOE in March 2006. This RDI plan covers all engineering disciplines for the program for a period of approximately four and one-half years. The first eighteen months of the plan cover Phase 1 (cycle optimization, conceptual design, cost & feasibility studies), and the remaining three years cover Phase 2 (detailed design of turbomachinery, design validation testing, and materials and process development).

The program schedule required that the RDI plan be written concurrently with the Cycle Optimization task, before it was known which cycle would be selected for further development. In order to ensure that sufficient resources were planned, the RDI plan was written around the expected conditions of the most challenging cycle which is the long term cycle.

The technical areas described in the RDI plan are as follows:

- Cycle optimization
- High temperature, intermediate pressure (IP) turbine for steam and CO₂ mixture (applies to all cycle arrangements)
- 760° C (1400 °F) high pressure (HP) turbine for the bottoming cycle in the combined Rankine cycle and the hybrid cycle (100% steam as the working fluid)
- 760° C (1400 °F) HP turbine for the direct cycle (steam and CO₂ mixture as the working fluid)
- Materials and processes required for all turbines
- Cost and feasibility studies leading to the selection of one concept for Phase II
- Detailed design of turbo machinery for one selected cycle
- Design validation testing

The planned work breakdown structure (WBS) corresponding to these technical areas is shown as four main tasks: Cycle Optimization, Conceptual Design of Equipment, Cost and Feasibility Studies, and R & D Implementation Plan. Subtasks under each of these tasks are listed in Tables 3-1, 3-2, 3-3, and 3-4, respectively. The full WBS includes all subtask titles along with their durations and the milestones.

Table 3-1 – Work Breakdown Structure for Cycle Optimization

1.1	Cycle Optimization
1.1.1	Previous cycle studies/ Reviews
1.1.2	Develop Design Interface Document with CES
1.1.3	Generate load models for aux systems (O ₂ Separation / CO ₂ Compression)
1.1.4	Combustor System Pressure vs Cost (Input)
1.1.5	Review of CES selected cycles
1.1.6	Cycle Concept Selection Meeting with CES
1.1.7	Cycle Development and analysis
1.1.8	Generate cost models for 3 cycles
1.1.9	Finalize three cycles to Analyze
1.1.10	Peer review of Task 1.1

Table 3-2 – Work Breakdown Structure for Conceptual Design of Equipment

1.2	Conceptual Design of Equipment
1.2.1	Conceptual Design – Baseline
1.2.2	Conceptual Design - Near Term
	1.2.2.1 620 Deg C Temp Turbines (Steam/CO ₂)
	1.2.2.2 High Temp. IP Turbine (Steam/CO ₂)
1.2.3	Conceptual Design - Long Term
	1.2.3.1 760 Deg C Temp Turbines (Steam/ CO ₂)
	1.2.3.2 High Temp. IP Turbine (Steam/ CO ₂)
1.2.4	Define material Requirements for each cycle
1.2.5	Detailed Review of Current Materials
1.2.6	Review Advanced High Temp Materials for suitability
1.2.7	Review manufacturing processes for Advanced Materials
1.2.8	Peer review of materials development plan
1.2.9	Conceptual design of valve
1.2.10	Combustor/Auxiliary Design - Baseline (Input)
1.2.11	Combustor/Auxiliary Design - Near term (Input)
1.2.12	Cooled IP Turbine Secondary Flow System Design
1.2.13	Combustor/Auxiliary Design - Long term (Input)
1.2.14	Examine steam & CO ₂ effects on GT materials
1.2.15	Turbine Component Cooling System Designs
1.2.16	CO ₂ /Heat Transfer Design - direct cycle
1.2.17	CO ₂ /Heat Transfer Design - indirect cycle
1.2.18	CO ₂ System Vendor interface
1.2.19	HRSG system vendor interface
1.2.20	Complete conceptual design of equipment for 3 cycles
1.2.21	Peer review of Task 1.2

Table 3-3 – Work Breakdown Structure for Cost and Feasibility Studies

1.3	Cost and Feasibility Studies
1.3.1	Turbo machinery Costs
1.3.2	Combustor/Auxiliary Cost (Input)
1.3.3	CO ₂ /Heat Transfer cost
1.3.4	Gasifier cost
1.3.5	ASU cost
1.3.6	HRSG cost
1.3.7	Design materials test loop
1.3.8	Build/commission materials test loop
1.3.9	Materials development & testing
1.3.10	Feasibility and Uncertainty Analysis
1.3.11	Cycle Selection (input to RDI plan)
1.3.12	Recommendations & Direction Forward
1.3.13	Go/No-Go Decision from Review of Task 1.3
1.3.14	Prepare Phase I final report
1.3.15	Submit Phase I final report
1.3.16	Development Support of Feasibility Studies

Table 3-4 – Work Breakdown Structure for R & D Implementation Plan

1.4	R & D Implementation Plan
1.4.1	Prepare R&D Implementation plan
1.4.2	Submit R&D Implementation plan to DOE
1.4.3	DOE review of R&D Implementation plan
1.4.4	Revise R&D Implementation Plan as needed
1.4.5	Resubmit R&D Implementation plan to DOE

4.0 CYCLE OPTIMIZATION

The purpose of the Cycle Optimization task was to update results from a limited number of previous system studies and identify the likely operating conditions of the turbines in those optimized cycles. This approach required that the combustion and turbine components be optimized together to determine the optimal pressures and temperatures for the complete cycle, including the thermal conditions that define the bottoming cycle.

Clean Energy Systems (CES) had primary responsibility for cycle optimization, with Siemens providing technical support in turbine technology, especially in regard to steam-Rankine bottoming cycles. The modeling aspects of the oxy-syngas plant cycles were reported by CES under their award DE-FC26-05NT42645.

4.1 Time-Phased Approach

The primary focus for chronological incorporation of R&D is the temperature of the working fluid at the turbine inlet. Gradual incorporation of higher working fluid temperatures in turbine designs is necessary to avoid potential operational issues, particularly due to the demand placed on materials over long periods of time under increasingly aggressive conditions.

For this study, three classes of cycles were analyzed: baseline, near term, and long term.

- The “Baseline” cycle represents a technology level that could be designed, manufactured, and available as commercial offerings in 2006. The baseline cycle was an ultra-supercritical steam cycle, in which the CES combustor gases transfer heat through a HRSG to a secondary loop of steam.
- The “Near Term” cycle represents a technology level that could be designed, manufactured, and available as commercial offerings in 2010. Near Term cycles feature high-temperature oxy-fuel turbines that use steam-CO₂ mixtures as working fluids and provide exhaust heat for a Rankine bottoming cycle. The near term bottoming cycle is an extension of current ultra-supercritical designs with emphasis on realistic near-term achievements and acceptable increases in risk.
- The “Long Term” cycle represents a technology level that could be designed, manufactured, and available as commercial offerings in 2015. The goal of the Long Term Cycle is to reach DOE goal of 50% to 60% (HHV basis) efficiency by incorporating concepts from the latest advanced gas turbine frames.

The operating conditions for each time phase are summarized in Table 4-1, along with their bases.

Table 4-1. Summary of Working Fluid Conditions Defined for Time-Phased Cases

Case	Baseline	Near Term	Long Term
High pressure steam turbine			
Maximum Inlet Temperature (Note 1)	593 °C (1100 °F)	620 °C (1148 °F)	760 °C (1400 °F)
Maximum Inlet	350 bar (5075 psia)	350 bar (5075 psia)	350 bar (5075 psia)

Case	Baseline	Near Term	Long Term
Pressure (Note 1)			
Basis	Use of current steam turbine technology without additional R&D	Allows a stretch of approx. 25°C in inlet temperature from current technology without significant changes in materials of construction	Current U.S. DOE program on ultra-supercritical steam turbine materials technology targets this temperature

Intermediate pressure “gas” turbine			
Maximum Inlet Temperature (Note 1)	-	1450 °C (2642°F)	1760 °C (3200°F)
Maximum Inlet Pressure (Note 1)	-	43 bar (624 psia)	43 bar (624 psia)
Basis	-	Allows sufficient time to incorporate current (natural) gas turbine materials technology to a new working fluid without exceeding the inlet temperature	Efficiency gain is the primary focus. Significantly higher temperature might help in this regard

Note 1: The numbers shown for working fluid temperature and pressure represent only the maximum achievable and do not indicate final selected conditions for design of turbines.

4.2 Candidate Cycle Configurations

There are four basic ways to arrange oxy-fuel combustors and the turbines, as illustrated in Figures 4-1, 4-2, 4-3, and 4-4. Figure 4-1 shows the indirect cycle, which represents current commercial technology and is used as the Base line cycle. Figure 4-2 shows the direct cycle, in which the combustor exhaust fluid flows directly through all turbines. Siemens and CES have chosen to call this the direct Rankine cycle. Figure 4-3 depicts the combined Rankine cycle wherein the exhaust fluid enters one high-temperature IP turbine directly, and heat recovery steam generators (HRSG) transfer heat from the primary loop to a secondary loop that drives conventional HP, IP and LP steam turbines. Figure 4-4 combines features from both previous arrangements to produce a hybrid cycle.

Figure 4-1. "Indirect" Cycle (Baseline)

Figure 4-2. The Direct Rankine Cycle

Figure 4-3. The Combined Rankine Cycle

Figure 4-4. The "Hybrid" Cycle

4.3 Initial Cycle Selection

In selecting the initial cycles for further study, CES had the modeling responsibility, and Siemens worked with Florida Turbine Technologies (FTT) to coordinate the capabilities of turbomachinery components with the drive gas conditions developed by CES.

CES and Siemens (2006) co-authored a white paper that described the most promising near term and long term cycles, and identified the near term and long term assumptions on which those selections were based. This white paper is included at the end of this report as Appendix II. After subsequent adjustments, the best long-term cycle was determined to be direct Rankine cycle with the drive gas conditions shown in Figure 4-5.

Figure 4-5. Selected Long Term Cycle

CES modeled the selected long term cycle in *ASPEN* using drive gas conditions in Figure 4-5 and other plant factors. The simulation results are shown in Table 4-2.

These conceptual results treated the combined IP and LP oxy-fuel turbines as a single expansion unit operating between a 42.7-bar inlet and a 15-millibar exit. Subsequent equipment design divided this component into the separate IP and LP turbines described under Conceptual Design of Equipment in this report.

Table 4-2. Long-Term Cycle Performance

Coal Thermal Input (MWt)	1388.0
Coal Thermal Input (MMBtu/hr)	4737.2
Power Output (MW)	724.8
HP Steam/CO ₂ Turbine	47.5
IP Steam/CO ₂ Turbine	677.3

Total Auxiliary Load (MW)	230.4
HP Syngas Compressor	5.0
IP Syngas Compressor	5.0
HP O ₂ Compressor	2.2
IP O ₂ Compressor, serving gasifier and IP combustor	40.8
Combustor ASU Load	44.6
Gasifier ASU Load	24.8
CO ₂ Compressor	86.4
N ₂ Compressors	1.3
Other Gasifier Loads	3.0
AGR Load	3.2
BOP Loads	14.2
Net Power Output (MW)	494.4
Net Efficiency (HHV)	35.6%
Net Heat Rate (Btu/kWh)	9,582

4.4 Program Redirection

Funding limitations starting in 2007 caused the focus and objective of the project to be changed. The original plan to develop turbines for the highest efficiency long term cycle was replaced by a revised plan that focused on the less complicated near term cycle that used a modified version of the Siemens SGT-900 gas turbine as its IP oxy-fuel expander. In 2008, a White Paper produced by Siemens and CES (and included as Appendix I to this report) gives a more detailed description of this change in focus.

4.5 Alternate Power Cycles (UC-I)

In the third quarter of FY2008, Siemens asked the systems analysis group at the Advanced Power and Energy Program (APEP) of the University of California, Irvine to develop overall system simulations of two oxy-combustion cycles for Zero Emissions Power Plant (ZEPP) applications -- one in natural gas application and the other in IGCC application. The APEP model used cycle parameters that were consistent with the natural gas fired "Gen 2 cycle" developed by CES, and performance parameters for the high-pressure and intermediate-pressure expanders that were consistent with parameters developed by Siemens and Florida Turbine Technology (FTT). The IP turbine model was based on design conditions for the expander in an SGT-900 turbine when operating with a steam/CO₂ mixture working fluid. The IGCC model also included performance parameters for a "warm gas cleanup" syngas conditioning process as provided by its developer, Research Triangle Institute (RTI).

APEP researchers used the basic configuration shown in Figure 4-6 for both the natural gas and IGCC cycles, but selected normal pentane (n-C₅H₁₂) instead of steam as the working fluid for the Rankine bottoming cycle. APEP (2009) presented the full results of this simulation study as a technical report that is included as Appendix III to this report.

Figure 4-6. Alternate Cycle with Organic Bottoming Cycle

The design and performance parameters for the two alternate cycles are compared with simulation results for the long-term cycle in Table 4-3. Oxy-fuel plant net efficiencies are estimated to be 25 to 30% for the near-term alternate cycles, and 36% for long-term cycle.

Table 4-3. Long Term and Alternate Cycles

Cycle Cycle Fuel	Long-Term IGCC IGCC Syngas	Alt-IGCC IGCC Syngas	Alt-NG Natural Gas
Topping Cycle			
Working Fluid	H ₂ O+CO ₂	H ₂ O+CO ₂	H ₂ O+CO ₂
HPT Inlet Temperature	760 °C (1400 °F)	538 °C (1000 °F)	538 °C (1000 °F)
HPT Inlet Pressure	103 bar (1495 psia)	83 bar (1200 psia)	83 bar (1200 psia)
Topping Reheat?	Yes	Yes	Yes
IPT Inlet Temperature	1760 °C (3200 °F)	996 °C (1825 °F)	996 °C (1825 °F)
IPT Inlet Pressure	43 bar (625 psia)	16 bar (230 psia)	16 bar (230 psia)
Bottoming Cycle			
Working Fluid	-	n-C ₅ H ₁₂	n-C ₅ H ₁₂
Plant Performance			
HPT Power	47.3 MWe	39.6 MWe	51.3 MWe
IPT Power	677.3 MWe	129.3 MWe	141.2 MWe
LPST Power	-	4.5 MWe	-
LP ORCT Power	-	18.9 MWe	28.3 MWe
Syngas Expander	-	3.0 MWe	-
Gross Power	724.8 MWe	195.2 MWe	220.8 MWe
Auxiliary Load	230.4 MWe	74.0 MWe	64.3 MWe
Net Power	494.4 MWe	121.2 MWe	156.4 MWe
Thermal Input (HHV)	1,388.0 MWt	478.1 MWt	506.3 MWt
Net Efficiency (HHV)	35.6%	24.5%	30.6%

4.6 References

Clean Energy Systems, Inc. and Siemens Power Generation, *Siemens Power Generation (SPG) and Clean Energy Systems (CES) Position on Long Term Possibilities for Efficiency Improvement of Power Plants Based on Oxy-Fuel Combustion and 100% Capture of Carbon-Dioxide*, white paper submitted to DOE-NETL, June 12, 2006.

Siemens Power Generation and Clean Energy Systems, Inc. *Proposal for the Future Scope of Turbine Development and Combustor Development for Oxy-Fuel Cycle*, Awards DE-FC26-05NT- 42646 and DE-FC26-05NT- 42645, white paper submitted to DOE-NETL, July 29, 2008.

University of California, Irvine, *ZEPP Cycle Performance on Natural Gas and in Coal Gasification (Full and Partial Quench Cases)*, Prepared by Advanced Power and Energy Program, August 2009.

5.0 CONCEPTUAL DESIGN OF EQUIPMENT

Turbo machinery development for a high-efficiency oxy-fuel cycle offers many technical challenges in turbine design and materials engineering. The unique working fluid with temperatures higher than either the current gas turbines or steam turbines requires close scrutiny of the design philosophy, design tools, materials selection strategy, testing techniques, and manufacturing methods. This section describes the technical challenges and proposed solutions that were applied to baseline, near term, and long term design concepts.

5.1 Cycle and Turbine Overview

Conceptual designs included turbines from three time periods: baseline, near term, and long term. The baseline cycle and turbines represent currently available technology, in this case for the year 2006. The baseline cycle is an 'indirect' cycle whereby oxy-fuel combustor gases exchange heat in a Heat Recovery Steam Generator (HRSG) with a secondary loop of steam. The secondary loop provides steam to the HP turbine at currently achievable temperatures as high as 593 °C (1100 °F). The reheat temperature entering the IP turbine would be the same as the main steam temperature. Materials of construction would be the same as those used in the current line of Siemens steam turbines.

The near term cycle and turbines represent designs that would be commercially available about five years in the future. In this cycle, the temperature capability (Turbine Inlet Temperature) of the IP turbine could be as high as 1450 °C (2650 °F), and the HP turbine inlet temperature could be as high as 630 °C (1165 °F). Materials of construction would be modified for presence of CO₂ and H₂O.

The long term cycle and turbines represent designs that could be commercially offered about 10 years in the future. This cycle is designed for maximum cycle efficiency. The IP turbine inlet temperature would be as high as 1760 °C (3200 °F), and the HP turbine inlet temperature would be as high as 760 °C (1400 °F). Materials development would be more ambitious than for the 'near term' turbine, with break-through advances expected in Thermal Barrier Coatings (TBCs), cooling technologies, ceramics, powder metallurgy and other areas. Materials of construction would be modified for presence of CO₂ and H₂O at elevated temperatures.

The maximum turbine inlet temperatures and pressures listed in Table 4-1 were originally selected to represent current, near term, and long term technological capabilities. Subsequent optimization efforts resulted in adjustments to the near term and long term cycles that yielded superior thermal performance without needing all of the maximum conditions. The resulting turbine inlet conditions for all three cycles are listed in Table 5-1, and the cycles and turbines are further described following the table.

Table 5-1. Time Phase Turbine Inlet Conditions

Time horizon	Now	5 years	10 years
Cycle Designation	Baseline	Near Term	Long Term
HPT working fluid	Steam	Steam	Steam-CO ₂

Time horizon	Now	5 years	10 years
Cycle Designation	Baseline	Near Term	Long Term
HPT temperature	520 °C (968 °F)	580 °C (1076 °F)	760 °C (1400 °F)
HPT Pressure	163 bar (2365 psia)	150 bar (2175 psia)	103 bar (1493 psia)
HPT Design basis	Steam turbine	Steam turbine	Steam turbine
IPT working fluid	Steam	Steam- CO ₂	Steam- CO ₂
IPT temperature	520 °C (968 °F)	1180 °C (2156 °F)	1760 °C (3200 °F)
IPT Pressure	32 bar (465 psia)	15.5 bar (225 psia)	43 bar (625 psia)
IPT Design basis	Steam turbine	Gas turbine	Gas turbine
LPT Working fluid	Steam	Steam	Steam-CO ₂
LPT Temperature	-	153 °C (307 °F)	760 °C (1400 °F)
LPT Design basis	Steam turbine	Steam turbine	Steam turbine

5.2 Baseline Turbine Parameters

The baseline cycle and turbines are shown schematically in Figure 5-1. Throttle and reheat steam conditions represent the results of cycle optimization, and they are within the capabilities of turbines in this time frame.

Coal to Grid Cycle η on HHV basis = 10.9%

Figure 5-1. Baseline Cycle and Turbines

Baseline turbine parameters provide reference data against which the corresponding parameters for near term and long term turbines can be compared. The boundary conditions for the baseline HP, IP, and LP turbines are summarized in Table 5-2.

Table 5-2. Baseline Steam Turbine Boundary Conditions

Main steam inlet pressure	162.5 bar	2,357 psia
Main steam inlet temperature	520 °C	968 °F
HP Turbine exit (cold reheat) pressure	33.6 bar	487.3 psia
Reheat steam pressure	31.8 bar	461.2 psia
Reheat steam temperature	520 °C	968° F
Crossover pressure	3.5 bar	50 psia
LP steam No. 1 admission enthalpy	2898 kJ/kg	1,246 Btu/lb
LP steam No. 2 admission enthalpy	2871 kJ/kg	1,234 Btu/lb
Condenser pressure	40 mbar	1.2 in.Hg

Figure 5-2 shows the longitudinal layout of the baseline turbines, which are three commercial turbine models within five casings.

Figure 5-2. Baseline Turbine Arrangement

The baseline turbines produce a total of 433 MW of electric power.

- The baseline HP turbine is the Siemens H36-40, a single-flow turbine with 22 stages and an 85.9 percent overall stage efficiency.
- The baseline IP turbine is the Siemens M36-63. This is a double-flow turbine with 17 stages in each flow path and a 93.8-percent overall stage efficiency.
- The baseline LP turbine is the Siemens N36-6x10.3. This is a 6-flow turbine set (three double-flow turbines) with an 82.4-percent overall stage efficiency.

5.3 Near Term HP Turbine

The near term cycle and turbines are shown schematically in Figure 5-3. The boundary conditions represent the results of cycle optimization, and are within the capabilities of turbines in this time frame.

Figure 5-3. Near-Term Cycle and Turbines

The boundary conditions for the near term HP turbine can be accommodated by the commercially available SST-700 turbine, as shown in Table 5-3. The SST-700 is a dual casing geared turbine with impulse blading.

Table 5-3. Near Term HP Turbine Boundary Conditions

Near Term HP Turbine

HP Turbine inlet pressure	150 bar	2,176 psia
HP Turbine inlet temperature	580 °C	1076 °F
HP Turbine exit (cold reheat) pressure	31 bar	450 psia

SST-700

HP Turbine inlet pressure	165 bar	2,395 psia
HP Turbine inlet temperature	585 °C	1085 °F
HP Turbine exit (cold reheat) pressure	40 bar	580 psia

5.4 Near Term IP Turbine

The oxy-fuel Rankine cycle poses several new challenges to the design of the IP turbine. To achieve the overall efficiency goals of the oxy-fuel system, the inlet temperature of this turbine must be substantially increased relative to typical levels in conventional installed steam turbines. This oxy-fuel turbine design therefore required the integration of advanced, high-temperature materials and cooling technologies found more commonly in aircraft jet engines and industrial gas turbines. As such, the IP turbine is considered to be a gas turbine, as opposed to a steam turbine, such as those found in the bottoming cycles of modern-day combined cycle installations where the working fluid is 100% steam.

Table 5-4 lists the original design goals for the Near Term IP turbine, which represented modest extrapolations of current gas turbine technology.

Table 5-4. Near Term IP Turbine Original Inlet Conditions

IP Turbine inlet pressure	43 bar	624 psia
IP Turbine inlet temperature	1450 °C	2640 °F

In 2007, the program was redirected to align with the reduced funding level for FY08. As a result, design work on the IP turbine focused on a lower temperature gas turbine from the Siemens mature product portfolio.

Several existing gas turbines were considered for this project, including a variety of manufacturers' models, sizes and mechanical arrangements. Final selection of the Siemens SGT-900 shown in Figure 5-4 was based on the turbine size, rated temperature and pressure conditions, use of a cooled turbine, and technical data availability.

Figure 5-4. Conventional Siemens SGT-900 Gas Turbine Engine

The turbine inlet conditions of the B11/B12 configurations of the SGT-900 are listed in Table 5-5. The speed rating is 5400 rpm, and a typical installation includes a gearbox that is used to drive a 60Hz generator producing 50MWe.

Table 5-5. Conventional SGT-900 Gas Turbine Boundary Conditions

IP Turbine inlet pressure	15.3 bar	225 psia
IP Turbine inlet temperature	1080 °C	1976 °F
IP Turbine exit pressure	1.1 bar	16 psia
IP Turbine exit temperature	1149 °C	957 °F

CES independently evaluated the use of this turbine with their oxy-fuel combustor with natural gas as the fuel, and Siemens evaluated the feasibility of using the design and materials from this “gas” turbine in a steam/CO₂ atmosphere. This near-term oxy-fuel combustion application of the SGT-900 turbine maintains a link to the attributes of the higher temperature turbines necessary for the long-term cycle. This machine was judged to require the least modification based on the existing gas turbine environment being most consistent with expected oxy-fuel power plant needs.

Adaptation of the SGT-900 gas turbine to provide power in oxy-fuel power plants included consideration of the impact and ramifications to the mechanical arrangement, aerodynamic behavior of the primary hot gas flow path, and thermal and chemical exposure of the turbine components to the alternative working and cooling fluids. The turbine design task resulted in the conceptual design, geometry and preliminary thermal and mechanical analysis of the stage 1 blade at the predicted base load operating conditions. The turbine design task also undertook an effort to improve turbine heat transfer predictive capability with the use of computational fluid dynamics (CFD) modeling.

Conversion of the Siemens SGT-900 turbine to the OFT-900 sketched in Figure 5-5 requires 13 major modifications, including removal of the compressor, installation of eight reheat combustors in place of the normal combustors, and the design of a larger thrust piston to compensate for the loss of compressor thrust.

**Figure 5-5. SGT-900 Modified to become OFT-900
(OFT-900 above centerline, SGT-900 below centerline)**

The molecular weight, fluid density, heat capacity, and fluid expansion characteristics of oxy-fuel combustion products are different than those of air-fuel combustion products, which caused the inlet conditions of the OFT-900, shown in Table 5-6, to differ from those of the SGT-900.

Table 5-6. Near Term OFT-900 Inlet Conditions

IP Turbine inlet pressure	15.5 bar	225 psia
IP Turbine inlet temperature	1180 °C	2156 °F

5.5 Near Term LP Turbine

The LP turbine in the Near Term cycle is a prototype that is similar to current commercial LP turbines, except for a significant concern about erosion damage from moisture in the last two stages. The boundary conditions and last stage geometry for the near term LP turbine are shown in Table 5-7.

Table 5-7. Near Term LP Turbine Boundary Conditions

LP Turbine inlet pressure	5 bar	73 psia
LP Turbine inlet temperature	153 °C	307 °F
LP steam admission mass flow	13 kg/s	28.7 lb/s
LP steam admission pressure	0.3 bar	4.4 psia
LP steam admission temperature	69 °C	156 °F
Condenser pressure	40 mbar	1.2 in.Hg
Speed	3600 rpm	3600 rpm

Potential erosion due to moisture droplets poses the main design challenge facing the Near Term LP design. The last two stages of the Near Term LP turbine have 25% and 27% moisture content and Erosion Indexes (E) of 3.7 and 13.4, both of which indicate significant susceptibility to erosion. By comparison, typical erosion indexes for commercial turbines are between 0.5 and 1.0. The erosion indexes are high because of the low (1.2 °C) superheat of the LP inlet main steam and the lower (~0 °C) superheat of the admission steam,

The potential erosion from moisture is similar to the challenges that faced first-generation nuclear units, which had external moisture separators but no steam reheaters. The solution for those units was to install internal moisture removal zones after rotating stages L-2R and L-1R, which are upstream from the second-last and last stationary vanes stages L-1V and L-0V, respectively. This solution could also be applied to the Near Term LP turbine. Three additional solutions to overcome erosion are:

- Slot and heat the L-0C and L-1 C vanes, although heating the steam might reduce the overall cycle enthalpy range.
- Flame-harden the L-1R and L-0R stages to make them more erosion resistant.

- Coat the L-1R and L-0R blades with an erosion resistant coating similar to the L-0R coatings in geo-thermal plants

These alternative approaches can be evaluated in greater detail during subsequent stages of development.

5.6 Long Term HP Turbine

The long term cycle and turbines are shown schematically in Figure 5-6.

Figure 5-6. Long-Term Cycle and Turbines

The boundary conditions shown in Table 5-8 represent the results of cycle optimization, and would be within the capabilities of turbines in this time frame.

Table 5-8. Long Term HP Turbine Boundary Conditions

Main steam inlet pressure	103 bar	1493 psia
Main steam inlet temperature	760 °C	1400 °F
HP Turbine exit (cold reheat) pressure	42.7 bar	619 psia
HP Turbine exit (cold reheat) temperature	599 °C	1110 °F
Cooling steam pressure	125 bar	1813 psia
Cooling steam temperature	560 °C	1076° F

The conceptual design of the long term HP turbine was developed with the help of CHAIN™ blade-path design software using the LibHuGas library of humid gas properties. Several decisions were made as a result of the CHAIN™ runs, such as:

- The operating temperatures of the rotor and inner casing at the inlet are hot enough at the inlet to need a nickel based super-alloy material.
- The operating temperatures of the rotor and inner casing at the exhaust are too high to use 1% Cr Steel.
- A nickel based super-alloy should be used for the rotor and inner casing, and a 10%Cr material should be used for the outer casing.
- External cooling will be used. Internal cooling will not work because the HP Exhaust is temperature is 610 °C (1130 °F), which is above the temperature capability of the outer casing material.

The conceptual design of the long term HP turbine has 17 stages, as shown in Figure 5-7, with blades ranging in height from 69 mm (2.7 inches) at the inlet to 138 mm (5.4 inches) at the exit. Waspalloy is proposed as the blade material.

The blade path has an inside diameter of 580 mm (22.8 inches), and an axial length of 1260 mm (49.6 inches). The design envelope of the turbine is similar to that of a commercial H36-25-25 Module.

Figure 5-7. Long Term HP Turbine Blade Path

Figure 5-8 shows the conceptual design of long term HP turbine with external cooling. A617 is proposed as the HP turbine rotor material because of its high creep resistance, good oxidation resistance, and potential weldability. These advantages are partially offset by its high material cost, difficult machinability, low yield strength, and a grain size that precludes the possibility of ultrasonic inspection. A617 is a nickel-based alloy that represents a departure from current practice and will require development for this application.

The inner casing is made of A625 material, another nickel-based alloy that is another departure from current practice. Like the rotor, the inner casing will require development for this application.

The outer casing material is X12, which is a 10% Cr steel that is not in use currently and would need development. The high exit temperature from the HP turbine requires the use of this material, since the 1% Cr steel is limited to 580 °C (1076 °F).

Figure 5-8. Long Term HP Turbine Conceptual Design

5.7 Long Term IP Turbine

The long term cycle features an oxy-fuel reheater that heats HP turbine exhaust to 1760 °C (3200 °F) and provides the 42.7-bar (619-psia) drive gas for the IP turbine. Cycle optimization activities in early 2007 simulated the IP and LP turbines as a single expansion unit operating between a 42.7 bar inlet and a 150-millibar exit, with an unprecedented expansion ratio of 284. As the turbines became better defined, an IP-LP crossover point was defined at 1 bar and 760 °C (15 psia and 1400 °C), giving the IP and LP turbines more reasonable expansion ratios of 42.7 and 6, respectively. The drive gas entering the separate, uncooled LP turbine expands to sub-atmospheric pressure of 150 millibars (2.2 psia = 4.35 inches of mercury). Inlet and exit boundary conditions for the IP turbine are listed in Table 5-9.

Table 5-9. Long Term IP Turbine Boundary Conditions

IP Turbine inlet pressure	42.7 bar	619 psia
IP Turbine inlet temperature	1760 °C	3200 °F
IP Turbine exit pressure	1 bar	14.5 psia
IP Turbine exit temperature	760 °C	1400 °F

The IP turbine is the most challenging turbo machinery component in the long term cycle. As such, most of the effort to date has been devoted to identifying the design

challenges associated with the IPT. The highlights of the conceptual design of the IPT are described below with the help of a longitudinal cross section shown in Figure 5-9.

Figure 5-9. IPT Cross Section Showing Primary Flow Path and Steam Cooling

Seven stages are required to expand the steam/CO₂ drive gas to atmospheric pressure. All stages of the IPT will be open-loop steam cooled, except for three vane stages that are conceptualized as made of a ceramic matrix composite (CMC) that will require minimum cooling.

5.8 Long Term LP Turbine

The LP turbine for the long term cycle expands the 1-bar (15-psia) steam/CO₂ exhaust from the IP turbine and delivers it to a condenser operating at 150-mbar (4.35 in.Hg) condensing pressure, as listed in Table 5-10.

Table 5-10. Long Term LP Turbine Boundary Conditions

IP Turbine inlet pressure	1 bar	14.5 psia
IP Turbine inlet temperature	760 °C	1400 °F
IP Turbine exit pressure	150 mbar	4.4 in.Hg
IP Turbine exit temperature	433 °C	811 °F

The LP turbine for steam/CO₂ working fluid is a new concept, and its expected 760 °C (1400 °F) inlet and 433 °C (811 °F) exhaust temperatures would be higher than temperatures in a “standard” low pressure steam turbine. The concept of the long term LP turbine has not been developed, but the design of such a turbine is not expected to pose major challenges. Upgrades in materials, such as upgrades to those used in gas turbines, might be required.

5.9 Technical Challenges for Detail Design

Subsequent design phases of the oxy-fuel turbines are expected to include significant design challenges, which are described within the categories listed below. Cost effective experimental approaches might be needed for the validation of key technologies.

Boundary condition challenges include the high inlet temperatures and pressures of the HP and IP turbines, especially for the long term cycles. Current steam turbines can accommodate pressures and temperatures as high as 310 bar and 595 °C (4500 psia and 1100 °F), and current gas turbines can accommodate pressures and temperatures as high as 20 bar and 1600 °C (300 psia and 3500 °F). However, commercial turbines cannot accommodate simultaneous combinations of high pressures and high temperatures, such as the 103-bar, 760 °C (1500-psia, 1400 °F) long term HP Turbine or the 43-bar, 1760 °C (625-psia, 3200 °F) long term IP Turbine.

Design software challenges are related to the novel working fluid mixture of steam and carbon dioxide. The two fluids have significantly different molecular weights, ratios of specific heats (gammas), and other thermodynamic and transport properties, which must be incorporated into existing design software for accurate predictions of expansion lines, heat transfer, and condensation. In addition, it might be advantageous to develop fluid dynamic similarity laws for CO₂ & H₂O for conceptual design.

Operation and control challenges include the ability to control stoichiometric combustion to produce the correct reaction products at both design and off-design conditions; the development of turbine control algorithms for off-design operation, transient operation, and by-pass operations; and the determination of start-up ramp rates for new materials that account for their differences in thermal conductivity and coefficient of linear expansion.

Cooling challenges include conceptual development of casing cooling, rotor cooling, and possible serpentine cooling circuits for the blades, as well as verification of cooling effectiveness calculations.

Materials challenges include determination of the chemical effects of CO₂ on the turbine materials due to phenomena such as carbonic acid corrosion, and the development of new materials such as wear-resistant coatings for the valves, high-temperature bolting materials, and Thermal Barrier Coatings (TBCs) with nickel-based super-alloys as substrate. Materials testing will include low cycle fatigue, creep fatigue, and stress cycle fatigue (crack growth) tests leading to calculations of life consumption for newly developed materials. Finally, new maintenance and inspection intervals will have to be developed for the design with newly developed materials.

Supply management challenges will concentrate on the development of suppliers who can supply newly developed materials in the required dimensions and sizes.

Development and design engineering challenges include the designs of HP and IP rotors and casings, possibly made from two dissimilar materials welded together; HP and IP valve designs, possibly with dual-metal casings; and HP and IP blading designs, possibly with new side-entry roots or larger diagonal stages. Development engineering will be needed for new high temperature sealing materials with special radial and axial clearances.

Turbines for the long term cycle have inlet temperatures and pressures approaching 760°C (1400 °F) and 350 bar (5075 psia), respectively, which would require designing a new HP/IP turbine for either the steam/CO₂ working fluid in the oxy-fuel topping cycle or

the pure steam in the bottoming cycle. Either way, the conditions are much more aggressive than those in currently available steam turbines.

To avoid heavily cooling these turbines, using the well understood conventional steam turbine design philosophy, the rotor and casing might consist of high-strength nickel-based super-alloy for the very high-temperature components, welded to the less expensive 9-12% chromium steels of the more moderate-temperature components. The relative differences in volumetric shrinkage between the two dissimilar alloys would complicate this welding. Austenitic stainless steels could not be used in such turbines because of their relatively large thermal expansion coefficients and lower thermal conductivity.

One solution to the dissimilar-metal welding problem is to divide both the HP and IP turbines into high-temperature and intermediate-temperature sections, and then combine the two high-temperature sections in one casing and the two intermediate-temperature sections in a separate casing, as shown in Figure 5-10.

The high-temperature portion would be made from the more expensive nickel-based superalloys, but it is expected to be relatively small compared to the intermediate-temperature portion that is made from high-chromium steel.

The high-temperature portion would be made from the nickel-based superalloys, and the intermediate-temperature portion would be made from the high-chromium steel. The more expensive superalloy turbines are expected to be small compared with the less expensive chromium-steel turbines.

Figure 5-10. HP/IP Turbines in High and Intermediate Temperature Casings

6.0 MATERIALS AND COATINGS EVALUATIONS

The drive gas in a normal gas turbine comprises 70 to 80 percent N₂ with minor fractions of O₂, H₂O and CO₂. In contrast, the drive gas produced for an oxy-fuel turbine comprises 80 to 90 percent H₂O with most of the remainder being CO₂. Testing was needed to validate the use of this new steam-CO₂ mixture in oxy-fuel turbines operating at design conditions with high temperatures.

In the proposed oxy-fuel cycles, the IP turbine operates at higher temperatures than either the HP or LP turbines, and therefore pose the most significant materials challenges. As originally conceived, the near term IP turbine inlet would operate at 1450 °C (2460 °F), and the long-term IP turbine inlet would operate at 1760 °C (3200 °F). In comparison, conventional steam turbine inlet temperatures are > 500 °C (~ 932 °F), and conventional gas turbine inlet temperatures are > 1300 °C (2372 °F).

The materials initially identified for various IP turbine components are listed in Table 6-1.

Table 6-1. Initial Identification of Materials for IPT Components

Component	Reference Material
Vane R1 and R2	CMSX4-SC or Modular PM2000
Vane R3	CM247-DS
Vane R4 –R6	Ceramic Matrix Composite
Vane 7	CM247-DS
Blade R1 and R2	CMSX4-SC
Blade R3-R7	CM247-DS
Ring segment R1	Haynes 214
Ring segment R2-R5	Ceramic Matrix Composite
Ring segment R6-R7	IN617 or Haynes 282
Transition pieces	Haynes 282
Exhaust case	IN617
Rotor	Steel and/or Ni-Cr alloys

Since CMC vane is a relatively new concept for Siemens, a concept study was undertaken for designs possible with CMC. Numerous possible concepts were discussed, analyzed and a limited number of these concepts were identified for further work.

Satisfying the requirements imposed on the materials and processes in developing these turbines is a substantial task. The long term steam turbines will require an operating temperature of at least 150°C (270°F) higher than today's supercritical steam turbines. Similarly, the IP gas turbine will require a turbine inlet temperature that is roughly 200°C (360°F) higher than those found on the most advanced power generation gas turbines today. The materials and process areas that pose particular challenges in this program are listed below in Tables 6-2 and 6-3.

Table 6-2. High Temperature IP Steam/CO₂ Turbine Development Challenges

Materials (super alloys or others) for the front stages of blades and vanes to enable higher temperatures

High specific creep strength alloys for longer blades in the back end of the IPT to improve efficiency

Higher temperature prime-reliant capability of thermal barrier coatings (TBCs) for blades, vanes and other critical areas. TBCs needed to prevent catastrophic material failures.

Environmental barrier coatings (EBCs) for steam/CO₂ mixture

Nickel alloy disc materials (temperatures will exceed the capability of conventional disc steels).

Specialized coatings (other than TBCs) to sustain even higher temperatures

Manufacturing of components with novel cooling features including highly complex 3-D cores

Table 6-3. HP and LP Steam Turbines Development Challenges

Different class of materials to handle higher temperatures along the blade path

Nickel alloy rotor in highest temperature zone

Dissimilar alloys joining in large cross sections (nickel based/steel)

Materials to sustain higher temperatures in large castings such as valve body and inner/outer casing

Specialized coatings normally used for other purposes to sustain even higher temperatures

Materials and related manufacturing considerations such as:

- Sealing materials in the blade path
- Bolting materials
- Chemical effects of CO₂ as well as those of sulfur, potassium and other contaminants
- Nickel based super-alloys with thermal barrier coatings (TBC) for steam turbine blading
- Development of a supply base to manufacture first-of-a-kind components

6.1 Program Redirection

Original materials investigations were aimed at the long-term IP turbine inlet conditions, but the program was redirected in FY 2008 to align with the reduced funding levels, and subsequent IP turbine design work focused on the lower temperatures of a mature Siemens gas turbine. However even though its inlet temperature was relaxed to 1180 °C (2156 °F), the IP turbine was still the most challenging element of the oxy-fuel turbine train, and materials studies focused on its operation with a high-temperature mixture of CO₂ and steam.

The first parts of this section describe work prior to FY2008:

- Review of current materials for long term application
- Review of advanced high temperature materials for long term application
- Review of advanced materials manufacturing processes for long term application
- Examination of steam and CO₂ effects on GT materials for long term application

The rest of this section describes work after the FY2008 realignment, focusing on the testing of normal turbine materials in oxy-fuel drive gas environments.

6.2 Review of Current Materials for Long Term Application

This review centered on the suitability of the materials currently used in gas turbines from a mechanical loading viewpoint. The temperatures and pressures in the IP oxy-fuel turbine are significantly beyond current industrial gas turbine experience, and many conventional materials would exceed their performance limits. For rotor components, with the availability of cooling steam from the bottoming cycle allowing reasonable temperatures to be achieved, steel rotor materials should still be realistic. This might be restricted by the need for significant improvements in sealing technology to prevent hot gas ingestion, and the increased risk for corrosion.

From a mechanical point of view, current directionally solidified (DS) blade alloys will remain suitable for the relatively cooler blades in stages 3 to 5. Due to the increased temperatures, it is likely that the later stages will need to be DS rather than conventionally cast. This would require significant improvements in casting technology as the final stage blade would be the largest ever to be cast our standard DS blade material.

The high pressure of the turbine inlet means that the front blade stages would be smaller than is common in Siemens gas turbines, facilitating the use of second-generation single crystal components in these rows. Were it not for the smaller component size, the increased complexity of the cooling configuration would prohibit the use of such materials. There is, however a significant risk of hydrogen embrittlement of these alloys, which will require significant research and changes in design philosophy to circumvent.

Current coatings and bond coats will not be adequate at the temperatures and temperature gradients at the hot end of the engine, but they will be suitable for the cooler stages further back in the engine.

6.3 Review of Advanced High Temperature Materials for Long Term Application

This review concentrated on materials and processing routes that are used in other industries, such as chemical processing or space rocketry, that might be applied to the oxy-fuel engine. Several materials options were considered, ranging from CMCs through refractory metals such as molybdenum and niobium alloys, to oxide-dispersion strengthened (ODS) superalloys.

The open literature has been searched and reviewed.

In terms of high temperature materials, Siemens historically adopted the nickel-base superalloys developed by the aerospace industry. Together with advanced thermal barrier coatings and film cooling, Siemens developed components capable of withstanding temperatures above 1300°C (2372°F) in the SGT6-6000G gas turbine. However, current technologies are not capable of meeting the anticipated temperatures of the oxy-fuel turbine program. In terms of material systems, nickel-base superalloys cannot be used where the metal temperature is expected to exceed 1100°C (2010°F). The principal phenomenon that provides a broad range of desirable properties to nickel-base superalloys is the unique behavior of its crystalline structure in the Ni₃Al (gamma prime) precipitate. Significant efforts have been made to provide other crystalline

structures in alloys of higher homologous temperatures, such as platinum-based systems. Other candidate high-temperature materials include ceramics and refractory alloys containing molybdenum, niobium, tantalum and others. These systems have been investigated for more than a decade but remain high risk because they represent a revolutionary step change. Essentially, many of these materials are prone to deleterious environmental degradation and tend to be characterized by low fracture toughness, particularly at intermediate temperatures. Successful use of these materials will depend on thorough design calculations. Siemens has already developed considerable expertise in ceramic compositions in systems being developed separately.

Material systems developed directly for space vehicle application have also been reviewed. As thermal spray technologies have improved, various material options, previously considered impossible to manufacture, have come to the fore.

6.4 Review of Advanced Materials Manufacturing Processes for Long Term Application

This review concentrated on the manufacturing difficulties likely to need addressing in the hot gas section of the IPT, which includes blades, vanes, disks, and ring segments.

6.4.1 Vane and Blade Applications

Cooling schemes might require advanced “skin cooling” concepts that have yet to be demonstrated in production for even advanced military aircraft applications. For the most complex components, such as the first-stage blade and vane, monolithic casting might not be possible.

The biggest impact on the reproducibility of the blades and vanes in this program is the complexity of the cooling scheme. Cooler-stage hot gas airfoils are at the size limit for directionally solidified products, with increased risk of material structure defects, excessive bulging, and excessive mold reaction. Fabricated vane approaches will be attractive for the larger vanes in this program. Alloy modification might be necessary to achieve satisfactory coating life, but that decision will follow a known development path. The manufacturing and design technology needs to be further developed for CMC’s in vane applications.

6.4.2 Disk Applications

Peak disk rim temperatures are expected to be around 450°C (840°F) for all seven stages of the turbine, due to the cooling gas fluid /heat balance with the gas stream. High chromium steels would normally be used, but the corrosive nature of the gas stream might prevent their use in oxy-fuel applications. Some superalloys under consideration are not typically processed in these sizes, and this size limit impacts the secondary manufacturing route (ingot/billet production) as well as final forming. Substantial capital investment, process development, and scale-up will be necessary to make this a production reality. Mechanical properties will be degraded below their expected levels due to manufacturing limitations and chemical segregation.

Conventional cast and wrought processing should be pursued. Isothermal forging and powder metallurgy processes are not available because the necessary equipment does not exist worldwide for disks this size. The sizes of the disks under consideration are at

the limits of the capability of the Industry. If the highest strength alloys are required, then incremental multi-step forging processes might be required. This approach will require multiple sets of dies at increased cost, although the use of process modeling might help to mitigate this situation.

6.4.3 Ring Segment Applications

There are no significant issues expected with metallic ring segments. Metallic parts can be easily cast and machined but might not have the temperature capability required. To improve the properties, new homogenization heat treatments might need to be developed, but this represents a very low risk. Should CMCs be needed, their manufacture would be considerably more challenging and complex, since novel attachment designs will be necessary and vapor barriers might be required.

6.5 Examination of Steam and CO₂ Effects on GT Materials

This review, designed as a generic overview of environmental effects has been used as resource primarily to identify the general risk trends. A secondary purpose was to identify the testing needs of the materials that will encounter the impure steam from the combustion process. Although there is a large body of work concerned with oxidation in steam or high water vapor content, it is difficult to extract coherent themes even within a single alloy class. The reasons are:

- Within current industrial situations, actual pure water vapor with a maximum oxygen partial pressure equal to its decomposition pressure is seldom, if ever, encountered.
- Atmospheres consisting of pure water vapor are very difficult to produce and maintain, thus reported observations within the literature are subject to caution.
- As a consequence of the two points already mentioned, much of the reported work deals with atmospheres consisting of O₂/H₂O, air/H₂O or H₂/H₂O mixtures.

Basic knowledge gaps relating to steam/ water vapor oxidation are reasonable given the complexities encountered. Further work is required to enhance the current level of understanding, in particular the influence of laboratory test procedures on the resultant data. Precise engine conditions are difficult or impossible to reproduce in the laboratory and some degree of simplification is necessary. Several exposure procedures are in common use in the laboratory. In ascending order of complexity these are:

- Water vapor in a carrier gas (argon or air)
- Flowing steam at atmospheric pressure
- Static steam at high pressure
- Flowing steam at high pressure

However, there have been few comparisons between the different techniques. Such a comparison between the different methods with in-service exposure would benefit the industry because it would give clear guidance about which method produces oxide scales that most closely resemble the oxide scales resulting from real exposures.

The review also showed that subtle changes in the alloy composition, such as the addition of Si or rare earth elements, can have marked effects on oxidation resistance in

steam atmospheres. Also, oxidation is a dynamic process and the presence of oxide scales will act to reduce the thermal diffusivity of components.

Nickel- and Cobalt-based Superalloys - Limited information exists in published literature regarding the steam oxidation resistance of nickel- and cobalt-based superalloys. The presence of water vapor adversely affects the selective oxidation of elements such as aluminum and chromium. Also, water vapor can cause the vaporization rate of some oxides to be increased because of the formation of hydrated species with high vapor pressures, and this characteristic is important for chromia formation.

Steels - Increasing the chromium content in steels improves their resistance to steam/water vapor oxidation. However, one of the most serious effects of water vapor on high-temperature oxidation is the increased spalling tendency for alumina and chromia scales.

Low alloy (1-3%Cr) Steels - Growth kinetics are affected by the flow rate of the steam atmosphere. The growth kinetic curves range from sub-parabolic at low temperature (500 °C, 930 °F) to almost linear at 650°C (1200 °F). The presence of water vapor in the test atmosphere can increase or decrease the corrosion rate, depending on test temperature.

Martensitic (9-12%Cr) Steels - The addition of silicon, titanium and yttrium to the alloys improves the steam oxidation resistance, while the addition of small (<1%) amounts of nickel reduces steam oxidation resistance.

Austenitic Steels - Oxidation rates increase under high pressure atmospheres. Fine grain size improves oxidation resistance by increasing the supply of chromium to the surface.

Further investigation into the effects of alloy composition changes could benefit future alloy development and plant design.

In conclusion, this review showed the need for systematic studies of the effects of alloy composition, laboratory test procedure, and steam chemistry on steam/water vapor oxidation behavior. Critical tests are required to establish the mechanisms operating in the different alloys and whether these mechanisms are affected by the experimental parameters. One possible route is through modeling and analysis of the steam atmosphere to determine the presence or absence of volatile species in the environment. Other critical measurements include the composition, microstructure, and growth kinetics of the oxides that are formed as functions of exposure, procedure, and alloy composition.

6.6 Kimberlina Initiative for Materials Coupon Exposure

Clean Energy Systems (CES) and Siemens initiated a small “piggy back” program to expose coupons representing the materials of the SGT-900 turbine hot gas path to the actual atmosphere of the 102-mm (4-inch) diameter combustor at Kimberlina. The advantage of this exposure is that the effects of the actual operating conditions of temperature and pressure will be seen on coupons.

In cooperation with CES personnel, a test rig was designed and constructed and delivered to CES's Kimberlina facility in February 2009. The first rig included four

uncoated coupons for a 50-hour shakedown test. The second rig included 11 coated alloys for the full 250-hour exposure test.

The gas stream for the 250-hour test comprised approximately 90 percent steam and 10 percent CO₂, with low-ppm concentrations of contaminants introduced into the gas stream (salt, sodium bicarbonate, erodent, and organic contaminant). As in the 50-hour test, significant deposits of these contaminants formed on the surface of the alloy coupons and on the rig itself.

Post-test inspection of the samples showed the deposition and oxidation behavior on the uncoated side of several coupons.

Figure 6-1 shows the oxide and contaminant formation on a bare IN939 surface. Similar to previous studies, there was significant formation of transient oxides and two distinct layers can be seen: a transient nickel oxide layer over a mixed oxide layer consisting of Ti, Ni, Cr, and Al oxides. As previously reported, these transient oxide formations are deleterious to growth of a stable protective oxide.

Figure 6-1. Contaminant Deposition and Oxide Formation on Bare Surface of IN939 Alloy

Figure 6-2 shows less extensive oxide formation on bare IN738 alloy; this was not previously observed in the 50-hour test, but was expected.

Figure 6-2. Contaminants on IN738 after 250 Hour Exposure.

The introduction of contaminants at the Kimberlina test site resulted in more degradation than in laboratory tests without the contaminants. Trace contaminants in the steam/CO₂ gas caused accelerated bond coat depletion, as seen on the left side of Figure 6-3. The bond coat on the X-45 alloy was fully depleted of Al-rich beta phase, there was cracking present within the bond coat and at the bond coat / alloy interface, and internal precipitates were also observed.

The Kimberlina tests demonstrated the importance of fuel cleanliness. The entire bond coat (left side) was depleted after 250 hours of exposure to the contaminated gas mixture, while the bond coat in the laboratory test sample (right side) showed only partial depletion after 250 hours exposure to gas without contaminants. Both tests were conducted at similar temperatures.

Figure 6-3. Bond Coat Depletion Due to Contaminants in Drive Gas

Bond coat depletion was also observed in the bond coat on the other alloys, but the extensive internal precipitation was not seen on the other alloys.

Exposure testing at the Kimberlina test site offered an opportunity to test coupon samples in an actual oxy-fuel environment at relatively low cost. The potential availability of this test facility offers a cost-effective path for characterizing material systems behavior in oxy-fuel environments.

6.7 Materials Validation in Oxy-Fuel Environment

In 2007 this program was redirected to align with the reduced funding level for FY2008. As a result, the program began to focus on converting a lower temperature gas turbine (SGT-900) from the existing Siemens product portfolio into an oxy-fuel turbine designated as the OFT-900.

A critical design consideration of the OFT-900 (expander portion of the SGT-900) pertains to the life of the components in the hot gas path of an oxy-fuel cycle. The SGT-900 was designed for, and is used commercially with, the products of natural gas combustion in air. A mixture of steam and CO₂ is a significant departure from the normal operating environment of gas turbine materials. The materials in the SGT-900 are:

- ECY-768 (cobalt-based alloy) with bond coat and TBC as the row 1 vane material
- IN738LC (nickel Inconel®) with bond coat and TBC as the row 1 blade material
- IN939 (nickel Inconel®) with bond coat and TBC as the row 2 vane material
- IN738LC (nickel Inconel®) with overlay coating only as the row 2 blade material
- X-45 (cobalt-based alloy) with overlay coating only as the row 3 vane material
- Udimet 520 (U520, nickel-based alloy) as the row 3 blade material
- 10325PN (3.5NiCrMoV high strength, low alloy steel) as the rotor material

The drive gas produced for an oxy-fuel turbine comprises 80 to 90 percent H₂O with most of the remainder being CO₂. Because of concerns that this oxy-fuel drive gas could degrade the surfaces of SGT-900 materials, they were analyzed and tested in the new environment in order to determine their viability.

An initial concern was the potential formation of carbonic acid ($\text{CO}_2 + \text{H}_2\text{O} \rightleftharpoons \text{H}_2\text{CO}_3$), but chemical equilibrium analyses of the drive gas showed that turbine operating conditions virtually precluded the formation of carbonic acid within the turbine.

The remaining concerns associated with the steam/CO₂ drive gas are due to its high H₂O content, which affects the formation of protective oxides on turbine materials. Turbine materials, specifically the nickel and cobalt base superalloys used in blades and vanes, have been developed over the past 50-60 years specifically for aero and industrial gas turbines. They were never initially intended to service in a high water vapor environment, thus, their performance in such an environment was an unknown. A material such as a nickel base superalloy is normally protected by a stable layer of oxide (chromia or alumina), but the higher H₂O content of the oxy-fuel drive gas increases oxide formation and can destabilize that protective layer. The higher H₂O content also has a similar effect on the oxide layer that protects bond coats.

Since the deleterious effects of the drive gas are most evident on material surfaces, testing focused on surface oxidation and low cycle fatigue (LCF), which begins as surface cracks. LCF test results determine fatigue life at various mechanical strains, and are particularly important because they provide the primary design data used to estimate turbine parts life. Five tasks were identified to address these issues.

1. Determine atmospheric bond coat limits for SGT-900 alloy/TBC combinations under standard test conditions to verify TBC spallation lifetimes.
2. Determine basic oxidation/corrosion behavior and characterization under defined steam/CO₂ conditions for SGT-900 alloy systems (substrate material, overlay coatings, bond coats and thermal barrier coatings).
3. Develop mechanical property test matrix for steam/CO₂ database to support critical design activities.
4. Identity critical test parameters based on above tasks and identify/develop a steam/CO₂ test facility.
5. Evaluation of direct metal fabrication process for modular components optimized for steam/CO₂ environments.

These tasks support the oxy-fuel combustion application of the SGT-900 turbine and maintain a link to the attributes of the higher temperature turbines necessary for the far-term cycle. The base metals, bond coats, thermal barrier coatings (TBCs), and rotor materials used in the SGT-900 were tested for their ability to operate in the steam- CO₂ environment of the oxy-fuel OFT-900.

Table 6-4 shows the tests performed on the turbine materials operating in the steam-CO₂ environment of the OFT-900.

Table 6-4. OFT Materials Testing

Base Alloy	ECY-768	IN738LC	IN939	X-45	Udimet 520	10325PN
Alloy Type	Cobalt	Nickel	Nickel	Cobalt	Nickel	NiCrMoV

Coating	Bond Coat + TBC	Bond Coat + TBC	Bond Coat + TBC	Overlay Coating Only	None	N/A
Internally Cooled?	Yes	Yes	Yes	No	No	
Application	Row 1 Vane	Row 1&2 Blades	Row 2 Vane	Row 3 Vane	Row 3 Blade	Rotor

Testing

Bond Coat Limits		X		X		
Spallation		X		X		
Corrosion.	X	X	X	X	X	
LCF, No-Hold, max temp [1]	X	X	X	X	X	X

Base Alloy	ECY-768	IN738LC	IN939	X-45	Udimet 520	10325PN
Alloy Type	Cobalt	Nickel	Nickel	Cobalt	Nickel	NiCrMoV

LCF, Hold time, max, intermediate, and room temps [2]				X	X	
Tensile				X	X	
Crack Growth						X

Notes:

[1] No-hold LCF tests subject samples to sinusoidal oscillations between tension and compression. In hold-time LCF tests, samples are held at maximum tension and compression points so the stress history more closely resembles a square wave instead of the sine wave of a normal LCF test. Hold-time LCF tests are performed in order to gain insight into the interactions between creep strength and fatigue strength.

[2] LCF tests at maximum, intermediate, and room temperatures were conducted only for Row 3 because the Row 3 operating temperature in the OFT has the largest temperature excursion from temperature of the same row in the SGT-900.

6.7.1 SGT-900 Alloy/TBC Atmospheric Bond Coat Limits

The durability of the TBC and bond coat was tested for the TBC-over-X-45 alloy and for IN738, which are the materials for the row 3 vane and rows 1 and 2 blades, respectively. These materials were chosen for testing because bond coat limits with these alloys and Siemens current standard bond coat (Sicoat2464) did not exist.

Testing consisted of thermally cycling the substrate alloy (IN738 and X-45) with bond coat and TBC top coat until TBC spallation (failure). TBC spallation tests were performed for the X-45 and IN738 alloys at three temperatures to generate spallation curves. This testing was done in air, not the steam/CO₂ mixture, because the baseline bond coat limits needed to be determined since the newer Sicoat2464 coating was not used on older frames with X-45 and IN738 alloys.

Test results for the X-45 and IN738LC samples are shown in Figure 6-4, where the upper curve represents IN738, the lower curve represents X-45, and the horizontal dashed line indicates 24,000 hours. The results indicated TBC lives of at least 24,000 hours for both materials, since the temperature at which 24,000 hour life is expected is much higher than the design temperatures in the OFT-900 oxy-fuel turbine.

Figure 6.4. TBC / Bond Coat Limits for X-45 and IN738 with Siemens Bond Coat and Standard TBC

6.7.2 SGT-900 Alloy Systems Oxidation/Corrosion

Oxidation and corrosion studies were performed for all blade and vane material systems in both steam/CO₂ and natural gas/air environments at Cranfield University in the United Kingdom. The gas composition selected for oxidation testing was 90% steam and 10% CO₂ by volume, simulating the approximate drive gas composition at the inlet of the OFT-900. Test temperatures were hotter than the expected temperature for the Row 1 Vane in order to obtain accelerated oxidation results. This testing was performed at atmospheric pressure for 500 hours with periodic removal of coupons to document weight change with time. When samples were received from Cranfield, the beta-phase (NiAl) depletion of the bond coats were measured by Scanning Electron Microscopy. Beta-phase depletion measurements are an indirect way to measure aluminum depletion in the bond coat, since the beta phase (which is rich in aluminum) depletes as aluminum diffuses into the thermally grown oxide and into the substrate alloy.

The results indicate that, for all alloys tested, the oxidation is more aggressive in a steam/CO₂ environment than in a typical gas turbine environment. This is seen in Figure 6-5 where samples exposed to the steam/CO₂ environment showed increased bond coat beta depletion (measure of oxidation). One reason for this bond coat depletion is the higher water vapor content of the drive gas, which interfered with the formation of protective oxide scales (Cr₂O₃ or Al₂O₃) and instead, formed the less-protective transient oxides. This effect can be seen in Figure 6-6, which compares the microstructure of a nickel-based superalloy after being exposed to a simulated oxy-fuel gas turbine environment (right) to that of a typical air-breathing gas turbine (left).

Figure 6-5. Bond Coat Beta-Phase Depletion on a Cobalt Substrate in a Gas Turbine Environment and Steam/CO₂ Environment

Figure 6-6. Microstructure of Nickel-Based Superalloy After Exposure in Simulated Gas Turbine Environment (Left) and Steam/CO₂ Environment (Right)

These results show that the operation of the OFT-900 with current SGT-900 materials would be viable. The corrosion / oxidation test results indicate that there is an effect on blade and vane oxidation, but it is not so great to preclude the use of these materials in the oxy-fuel environment at current design temperatures. Additional work has been proposed in a follow-on project to complete additional testing out to longer times (3,000+ hours) so the effect on turbine relevant lifetimes and service intervals (8,000 to 24,000 hours) can be conclusively determined.

6.7.3 Mechanical Property Test Matrix

Mechanical property testing comprised three types of tests: low cycle fatigue (LCF) for all materials, tensile tests for row 3 vane and blade materials, and crack growth tests for the rotor material.

6.7.3.1 Low Cycle Fatigue (LCF) Tests for Airfoil Materials

To assess the effect of the oxy-fuel environment on the blade and vane alloys, low cycle fatigue (LCF) tests were performed in air on steam/CO₂ exposed alloys. LCF specimens were exposed to 90% steam, 10% CO₂ by Cranfield University and the National Energy Technology Laboratory in Albany, Oregon. The effect of free oxygen (up to 0.2% O₂)

was considered and determined to be negligible on the oxidation of the steam/CO₂ environment. Specimens were exposed for 1,000 hours at the expected temperature of each stage in the hot gas path of the OFT-900. Specimens were coated as they would be in the SGT-900; using the material systems of the SGT-900 engine as shown in Table 6-5. In addition, to simulate the effect of steam/CO₂ on the cooling path of blades and vanes with internal cooling, bare alloy specimens were exposed at low temperature for alloys of cooled components.

Table 6-5. Blade and Vane Materials of the SGT-900 Turbine

Component	Row 1 Vane	Row 1 Blade	Row 2 Vane	Row 2 Blade	Row 3 Vane	Row 3 Blade
Base Alloy	ECY-768	IN738LC	IN939	IN738LC	X-45	Udimet 520
Coating	Bond Coat + TBC	Bond Coat + TBC	Bond Coat + TBC	Overlay Coating Only	Overlay Coating Only	None
Internally Cooled?	Yes	Yes	Yes	No	No	No

Initial results showed oxy-fuel exposure had little effect on the strain-life relationship in hot gas path conditions on either the coated (Row 1 and 2 blades and vanes, Row 3 vane) or the uncoated (Row 3 blade) alloy samples, as shown in Figure 6-7. Also, different effects were found at low temperatures on the uncoated alloys. Nickel-base alloys showed minor effects to the strain-life properties after oxy-fuel exposure, similar to the trend shown in Figure 6-7, whereas cobalt alloys showed a noticeable debit to strain-life properties at high strain ranges, as shown in Figure 6-8.

Figure 6-7. Strain-Life LCF Plot of Steam/CO₂ Exposed Cobalt Alloy (with Overlay Coating) at High Temperature versus Baseline Cobalt Alloy

Figure 6-8. Strain-Life LCF Plot of Steam/CO₂ Exposed Cobalt Alloy (No Coating) at Low Temperature versus Baseline Cobalt Alloy

LCF testing of both cobalt-bases and nickel-based alloys showed no significant deviations from baseline strain-lifetime curves at higher-temperatures, as shown in Table 6-6. At lower temperatures, however, cobalt alloys ECY-768 and X-45 exhibited substantial difference in from their baseline curves at high total strain ranges, while the nickel-based alloys IN738 and IN939 did not show these differences and remained aligned with baseline curves.

Table 6-6. Deviations from Baseline Strain-Lifetime Curves

Alloy Type	Target Operating Range	Nickel-based	Cobalt-based
Lower temperatures, lower total strain ranges	X	No significant deviations	No significant deviations
Lower temperatures, higher total strain ranges		No significant deviations	Significant deviations at high total strain ranges
Higher temperatures, lower total strain ranges	X	No significant deviations	No significant deviations
Higher temperatures, higher total strain ranges		No significant deviations	No significant deviations

6.7.3.2 Tensile Tests for Row 3 Vane and Blade Materials

Tensile tests were performed on cobalt-based X-45 and nickel-based Udimet 520, the row 3 vane and blade materials, in order to determine their ultimate and yield strengths. The specimens were exposed to steam/ CO₂ environments for 1,000 hours before testing. These two materials were selected for tensile testing because the tensile properties were needed for use in generation of Ramberg-Osgood and Coffin-Manson-Basquin coefficients for design models. The change in yield strength due to exposure at temperature is also an indication of embrittlement.

The results, shown in Figures 6-9 and 6-10, indicate no significant impact to the strength or tensile properties of X-45 and U520. Ultimate tensile strength (UTS) for X-45 at 538°C (1000 °F) was slightly lower than the average of virgin X-45 material, but the drop in strength is not significant since there was no correlated drop in the yield strength (YS). Neither material experienced a significant shift in yield strength after the oxyfuel exposure, so it can be concluded that no significant embrittlement or drop in tensile properties was seen during testing. This supports findings from the LCF testing that have shown that oxy-fuel exposure had little effect on the fatigue and strength properties of the alloys tested.

Figure 6-9. Tensile Results of X-45 Material Exposed to Steam-CO₂

Figure 6-10. Tensile Results of U520 Material Exposed to Steam-CO₂

6.7.3.3 Crack Growth Test for Rotor Material.

The effect of an oxy-fuel environment on the rotor material was determined by performing crack growth tests and comparing the results with results for materials in a conventional air environment. These fatigue crack growth tests were all completed at 300°C (570°F), and their results are shown in Figure 6-11. The clustering of data points shows that crack growth in the rotor steel exposed to steam/CO₂ was similar to crack growth in air, indicating that the presence of the oxy-fuel environment did not accelerate fatigue crack growth behavior for a low-alloy steel such as 3.5NiCrMoV.

It is not known if this crack growth behavior is similar for nickel and cobalt based blade and vane alloys, so a follow-on crack growth program to examine crack growth in environment of Blade 1 and 2 alloys IN738 has been proposed. Low-alloy steels similar to 3.5NiCrMoV are sometimes used in steam turbines, so the development of this steel is much more diverse than a typical gas turbine superalloy, which may be a major reason why it performed similarly in air and steam/CO₂ environments.

Figure 6-11. Crack Growth Rate in Oxy-fuel and Air

6.7.4 Steam/CO₂ Test Facility

While a test facility that is capable of providing steam/ CO₂ mixture at a higher pressure (about 10-15 bar) would come closer to matching the fluid conditions in the SGT-900 blade path, Siemens used an existing atmospheric test facility for exposure of the LCF specimens for this first evaluation. In addition to pressure, another parameter that has an undetermined effect on surface oxidation is the velocity of the steam/ CO₂ mixture as it impinges the specimen surface.

All of the facilities evaluated can generate the gas mixture only at atmospheric pressure without being able to control the velocity beyond a narrow range. Siemens discussed the need to vary these parameters with test facilities in the US and UK. As and when the need for testing increases substantially, this topic will be reopened with the test facilities.

6.7.5 Direct Metal Fabrication (DMF) Process Evaluation

This task evaluated the use of Mikrosm Tomo- Lithographic-Molding (TOMOsm) as an innovative method for the direct fabrication of nickel superalloy parts. The process involves casting and thermal processing of metal powders to produce a 3-dimensional, high definition part. The focal points of the program were low-pressure powder/binder development, thermal processing and measurement of properties.

A relatively low aluminum content superalloy (Haynes 230) powder was selected for initial development. Through this first development trial, densities of about 94% of theoretical were achieved with acceptable tensile properties. Final fired (sintered and

HIPped) parts were manufactured and delivered. Figure 6-12, below shows the parts in final configuration.

Figure 6-12. Examples of Direct Metal Fabrication Using Sintered Powders

In addition to the use of sintered powders to make direct fabrication parts, a second approach was to use TomoLithography directly to manufacture superalloy foils, which are then diffusion-bonded to make 3-dimensional parts. Haynes 214 foil was selected for this development. The same part configuration was used to demonstrate this approach, the end product of which can be seen in Figure 6-13.

Figure 6-13. Examples of Direct Metal Fabrication Using Diffusion Bonded Foils

Both approaches have demonstrated the feasibility of DMF.

6.8 Proposed Additional Testing

Tests performed under this program were long enough to establish the viability of the materials for the first short demonstration tests, but not long enough to validate the materials for years of continuous base load operation. Additional testing is therefore recommended to further calibrate the extent of life reduction during longer-term operation.

The corrosion properties of X-45, IN939, Udimet 520 (U520), and advanced alloys should be tested in steam-CO₂ environments for durations as long as 3,000 hours. These tests would characterize the effects on the OFT-900 that were not fully

characterized in this study, and would characterize selected advanced alloys that could provide increased durability in steam-CO₂ environments.

The mechanical properties of IN939, X-45, and CM247 should be compared for samples exposed to air, steam-CO₂, and natural gas environments. CM247 is a nickel-based alloy with high gamma-prime content that is currently proposed for the row 1 blades in a concurrent hydrogen turbine program. CM247 could substitute for the IN738LC or U-520 currently planned for the rotating blades in rows 1, 2, or 3 of the OFT-900 for future, higher-temperature oxy-fuel turbines. These mechanical property tests would build on previous testing to determine whether corrosion increases mechanical degradation. Argonne National Laboratory has the unique capability to test *in situ*, but was not used in previous years due to funding restrictions.

Vane 3 will operate at a higher temperature in the OFT-900 than it would in a standard SGT-900, potentially changing its LCF characteristics. No-hold and limited hold-time tests were completed under this program, and additional hold-time tests should be completed to account for stress relaxation and more realistic engine conditions.

LCF testing assesses life until crack formation, after which fracture mechanics (FM) testing assesses life after crack formation until failure. FM testing, which focuses on crack growth, has been performed on the rotor material, and this testing should be extended to airfoil material to assess remaining life after crack formation.

Table 6-7 identifies completed and proposed testing for expander airfoil and rotor materials operating in the steam-CO₂ environment of the OFT-900.

Table 6-7. Completed and Proposed OFT Materials Testing

Component	Row 1 Vane	Row 1 Blade	Row 2 Vane	Row 2 Blade	Row 3 Vane	Row 3 Blade	Rotor
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Description

Base Alloy	ECY-768	IN738LC	IN939	IN738LC	X-45	U520	10325PN
Coating	Bond Coat + TBC	Bond Coat + TBC	Bond Coat + TBC	Overlay Coating Only	Overlay Coating Only	None	N/A
Internally Cooled?	Yes	Yes	Yes	No	No	No	N/A

Testing

Corrosion.	500-hr tests done. 3,000-hr proposed	500-hr tests done. 3,000-hr proposed	500-hr tests done. 3,000-hr Proposed	500-hr tests done. 3,000-hr proposed	500-hr tests done. 3,000-hr Proposed	500-hr tests done. 3,000-hr proposed	
LCF, Hold time at max temp.					Done	Done	
LCF, No-Hold at max temp.	Done	Done	Done	Done	Done	Done	Limited testing done. Added testing proposed
LCF, No-Hold at intermediate temp.					Done	Done	Proposed
LCF, No-Hold at room temp.					Done	Done	Proposed
Tensile					Done	Done	
Crack Growth		Proposed					Done

Notes to the table:

ECY-768 with bond coat and TBC is the row 1 vane material
 IN738LC with bond coat and TBC is the row 1 blade material
 IN939 with bond coat and TBC is the row 2 vane material
 IN738LC with overlay coating only is the row 2 blade material
 X-45 (Cobalt) with overlay coating only is the row 3 vane material
 Udimet 520 (Nickel) is the row 3 blade material
 10325PN is the rotor material
 "Done" refers to tests completed under DE-FC26-05NT42646
 "Proposed" refers to tests proposed as follow-on work.

6.9 Materials Test Conclusions

The base metals, bond coats, thermal barrier coatings (TBCs), and rotor materials used in the SGT-900 were tested for their ability to operate in the steam- CO₂ environment of the oxy-fuel OFT-900. Test results indicated that these same materials would operate satisfactorily in the OFT-900, although with slightly reduced service lives. The plan for the OFT-900, therefore, is to use the same materials that were used in the SGT-900.

LCF testing of both cobalt-bases and nickel-based alloys showed no significant deviations from baseline strain-lifetime curves at higher-temperatures. At lower temperatures, cobalt alloys ECY-768 and X-45 exhibited substantial difference in from their baseline curves at high total strain ranges, but the nickel-based alloys IN738 and IN939 did not show these differences and remained aligned with baseline curves.

There is no effect on U520 material life after exposure to the oxy-fuel environment for 1,000 hours, and the low cycle fatigue life of this material in oxy-fuel application matched the baseline life as expected.

Tensile test results indicate no significant degradation of the strength or tensile properties of X-45 and U520 after exposure to steam/ CO₂ environments.

Crack growth of the rotor steel in a steam/ CO₂ environment matched the expected crack growth rate for a low-alloy steel such as 3.5NiCrMoV, so the presence of the oxy-fuel environment did not accelerate fatigue crack growth behavior.

Follow-on programs for corrosion testing to 3,000 hours in oxy-fuel environment and evaluation of the crack growth rate of Blade 1 and 2 alloy IN738 in environment have been proposed. These follow-on programs will build on the results presented here and provide a more conclusive and quantifiable assessments of the effects of oxy-fuel environments on the service lives of turbine components.

7.0 COST AND FEASIBILITY STUDIES

The economic analysis and market demand for oxy-fuel turbine cycle (OFTC) was performed by Science Applications International Corp. (SAIC), who utilized the National Energy Modeling System (NEMS) released by the Energy Information Agency. The confidential SAIC report was delivered to DOE in 2007, but this section summarizes the approach, assumptions, results, and conclusions from that analysis.

7.1 Technical Approach

The technical approach applied in this project relies on use of the National Energy Modeling System (NEMS) to respond to Siemens's goals. These goals were:

- Develop an appropriate methodology and related assumptions, using NEMS, to evaluate and project the competitive performance of the OFTC technology from 2015 to 2030.
- Develop a consistent baseline set of cost and performance assumptions for OFTC and competing coal-based technologies for use in NEMS.
- Identify, develop, and execute an appropriate set of NEMS baseline cases to project technology competitive performance (power generation market penetration) within a carbon-constrained framework from 2015 to 2030.
- Identify, develop, and execute an appropriate set of NEMS sensitivity cases to quantify the impact of some key technology cost & performance parameters, as well as exogenous methodology assumptions.
- Assess NEMS results for the baseline and sensitivity cases to help characterize key factors that will determine the viability of power generation by the OFTC technology within a carbon-constrained framework.

7.2 Assumptions

Siemens and SAIC worked together to arrive at reasonable assumptions for the capital cost, operational costs, and performance of the technology to be evaluated. The long term cycle is described in Section 4, and its performance is summarized in Table 7-1.

Table 7-1. Long-Term OFTC Performance Specification

Coal Thermal Input (MWt)	1388.0
Coal Thermal Input (Million Btu/hr)	4737.2
Power Output (MW)	724.8
HP Steam/CO ₂ Turbine	47.5
IP Steam/CO ₂ Turbine	677.3
Total Auxiliary Load (MW)	230.4
HP Syngas Compressor	5.0
IP Syngas Compressor	5.0
HP O ₂ Compressor	2.2
IP O ₂ Compressor, serving gasifier and IP combustor	40.8

Combustor ASU Load	44.6
Gasifier ASU Load	24.8
CO ₂ Compressor	86.4
N ₂ Compressors	1.3
Other Gasifier Loads	3.0
AGR Load	3.2
BOP Loads	14.2
Net Power Output (MW)	494.4
Net Efficiency (HHV)	35.6%
Net Heat Rate (Btu/kWh)	9,582

SAIC made additional assumptions about the commercial environment associated with a carbon-constrained economy. The OFTC technology is one that would only be used in a carbon-constrained environment since its capital and operating costs are much higher than competing technologies that emit CO₂, such as pulverized coal (PC) and IGCC technologies,. Therefore, this project required that NEMS be executed using one of its available carbon-constraint methods. The Carbon Dioxide Tax (Allowance Price Cap) method was selected for use in this project since some recent legislation calls for such an approach via a cap and trade standard with a “safety valve” acting as the maximum allowance price (carbon tax) allowed.

A baseline CO₂ tax profile was established to achieve a reference CO₂ emissions cap when executing the AEO2007 Reference Case (with baseline nuclear constraint). The carbon cap targets are based on the US government administration goal of reducing the CO₂ emissions intensity of the U.S. economy by 18 percent between 2002 and 2012, and a subsequent goal of reducing the carbon emissions intensity by about 50 percent from 2013 to 2030.

Two nuclear constraint scenarios were applied to the model to represent more realistic nuclear capacity addition. The baseline constraint allows more than a doubling of existing capacity (from 100 GW to 205 GW) by 2030, while an alternative scenario, which was used for the OFTC case runs, limits total capacity to less than 160 GW by 2030. The 160-GW scenario offers a more conservative and realistic outcome.

The project entailed development of consistent performance and cost input data for the OFTC, IGCC, ‘IGCC with sequestration’ (IGCC/S), natural gas combined cycle (NGCC) and ‘natural gas combined cycle with sequestration’ (NGCC/S) technologies. The results of this effort provided cost and performance data that are more conservative (higher) than either the NEMS default data or the OFTC cost estimate. Data were also developed for a pulverized coal-fired power plant with an amine-based CO₂ capture technology (PC/S) and for a natural gas oxy-fuel combined cycle (NGOC), both of which were also included in the modeling effort.

7.3 Results

The model indicated a preference for non-CCS (carbon capture and sequestration) alternatives such as renewables, nuclear and high-efficiency natural gas combined cycle plants. However, starting in 2025 when the CO₂ tax is assumed to reach \$40/ ton,

OFTC starts to look attractive. Over the following five years, it has a clear advantage over IGCC with sequestration and over PC (pulverized coal) with sequestration.

While the capital and O&M costs for the baseline OFTC technology were estimated to be higher than those of either IGCC/S or PC/S, three other factors combined to reduce the levelized COE for OFTC compared to those technologies, resulting in greater market penetration for OFTC (8 GW) than either IGCC/S (4.9 GW) or PC/S (0 GW). Those factors are:

- Significantly higher initial efficiency -- 35.6% for OFTC vs. 32.1% for IGCC/S and 26.9% for PC/S -- which reduces coal consumption and associated cost
- 10% higher CO₂ capture, which is the equivalent of reducing fuel cost by 10%
- Earlier market penetration due to lower levelized COE.

These factors also favor the OFTC technology by allowing market penetration earlier than the other two coal-based methods, as seen in Figure 7-1.

Figure 7-1: Relative Market Penetration as Predicted by NEMS Simulation

7.4 Sensitivity Analyses

Several sensitivity analyses were conducted to evaluate the effects of key assumptions on the market penetration of OFTC technology. These sensitivity analyses are highlighted below.

- **Reduced Efficiency** -- Reducing the plant efficiency from the base value of 35.6% to 33% increased the power-specific capital cost (\$/kW) and reduced market penetration in 2030 from 8 GW to 0 GW. The levelized COE consistently increased

by 5 to 6% across the time-frame. Reducing efficiency below ~35% is expected to eliminate market share for the baseline assumptions, which include the base CO₂ tax and nuclear constraints

- **Increased CO₂ Tax Profile** -- An alternative CO₂ tax profile, which allowed the NEMS projection to meet the baseline CO₂ cap, increased OFTC market share by 225% (8 GW to 26 GW) in 2030, and also advanced the introduction of the OFTC technology by three years – from 2024 to 2021.
- **Constrained Nuclear Capacity** -- When nuclear capacity is constrained to “only” doubling existing capacity (100 GW to 205 GW), less than 1 GW of OFTC capacity is projected by 2030 and introduction is delayed until 2029. When nuclear capacity is constrained to adding a maximum of 58 GW by 2030 (~ 58 plants in no more than 20 years), OFTC builds increase to 8 GW (16 - 500 MW plants).
- **Increased World Oil Price** -- Use of an alternative World Oil Price (WOP) (based on EIA's high WOP side-case), as well as natural gas import and transmission constraints that drive natural gas prices commensurately higher, advanced the introduction of the OFTC technology by four years – from 2025 to 2021 -- and increased OFTC market share by 165 percent, from 8 GW to 21.4 GW, by 2030.
- **Investment Tax Credit** -- Availability of a 20-percent investment tax credit (ITC) for the first 1.8 GW of installations advanced the introduction of the baseline OFTC technology by six years (2025 to 2019) and increased installed capacity by more than 3 GW relative to the case without the ITC
- **Natural Gas Oxy-Fuel Combined Cycle (NGOC)** – Natural gas-fueled technology can be commercialized earlier than the syngas-fueled OFTC, so two NGOC cases were investigated that incorporated a 15% combustion-based ITC and \$10/ton CO₂ sales credit. Using efficiencies based on the EIA 2007 *Annual Energy Outlook*, one case is a 45-percent efficient version available in 2015 for installation in 2018, and the other case is a 44--percent efficiency version available in 2011 for installation in 2014. However, the earlier availability of lower-efficiency version did not help its market penetration because of the smaller impact of carbon tax on natural gas prices. IGCC with sequestration also competes very effectively with the NGOC due to its early introduction in 2010, 20% ITC, and higher CO₂ capture and sequestration credits.

7.5 Conclusions

The capital cost associated with an oxy-fuel turbine plant is significantly higher than that of a comparable IGCC plant, but the oxy-fuel plant competes well because of an assumed carbon tax (\$10/metric ton starting in 2012 and rising to \$50/metric ton in 2030). If the carbon tax (or cap & trade, auction system) does not materialize, the plant is not competitive.

The sensitivity analyses indicated that insufficient carbon tax and lower efficiency could severely undermine or eliminate the commercial potential for OFTC technology. Further, if the efficiency of the plant falls much below 35%, the NEMS simulation indicated elimination of market penetration under the base assumptions made.

Natural Gas Oxy-Fuel Turbine Cycle (NGOC) captures about 14 GW of capacity between 2018 and 2030, but both IGCC with sequestration and OFTC build much

greater market shares due to their lower costs and greater impact of the CO₂ credits due to the production of much higher levels of CO₂ for sequestration.

8.0 RISK ASSESSMENT

The development of turbo machinery for zero CO₂ emission oxy-fuel combustion technology is an undertaking with significant technical challenges. In order to prioritize and quantify these challenges by their risks, a methodical approach was followed. The methodology is known as SIRA (for Siemens Risk Analysis) and it follows a process prescribed by the Project Management Institute (PMI). PMI is recognized as a Standards Development Organization by the American National Standards Institute (ANSI). The risk management process advocated by the PMI is contained in its PMBOK® (Project Management Book of Knowledge).

A workshop was conducted by Siemens Corporate Technology (Munich, Germany) personnel in Orlando with the oxy-fuel turbine development team. The risk analysis had two objectives: to identify the relative risks of this program compared to similar undertakings in the past as a management aid for business decisions such as R&D investment; and to help adjust and prioritize tasks, subtasks, and resources required in order to maximize the probability of project success.

The scope of the risk analysis comprised the combustor, HP turbine, re-heater, and IP turbine of the far term cycle, as shown in Figure 8-1. Other parts of the plant, such as the gasification island, were not included into the analysis.

Figure 8-1. Long Term Cycle - Risk Analysis Scope

Risks at interfaces were taken into account only if the influenced components were within the scope of the analysis – for example, the impact of fuel impurities on design life of hot gas parts due to corrosion. The analysis considered risks affecting plant operation as well as risks affecting the development.

8.1 Technical Approach

Figure 8-2 shows schematically the steps involved in various phases of the risk analysis and monitoring process. Specifically in regard to the turbine development program, the methodology involved the first three aspects: risk identification, risk evaluation, and risk mitigation.

sira Risk Analysis

Siemens specific risk analysis – 4 phases model

Figure 8-2: Details of Steps in Risks Evaluation Process

8.1.1 Risk Identification:

Prior to the workshop, the team members prepared various documents that provided the latest information regarding:

- Conceptual design of the turbines
- Engineering requirements of the turbines (design life, efficiency, availability etc.) and combustors
- The amount by which technology will have to be stretched compared to the current state-of-the-art (SOTA) for each turbine and combustor
- The scope of SIRA – boundaries of the turbo-machinery and its interfaces with the rest of the power plant

The workshop was conducted with approximately 15 stakeholders, about half of whom comprised the project team. The other participants were experts in gas turbine design, combustion, steam turbine design, and materials engineering. One component at a time was considered (such as the high temperature IP turbine), and the stakeholders were asked to identify their perspectives of the risks that the deployment of the component would not meet the identified requirements.

Using the risk identification process, the team identified approximately 120 “topics” consisting of both risks and uncertainties.

8.1.2 Risk Evaluation:

Each risk was considered for qualitative evaluation based on experience, judgment, and intuition on a scale from 0 to 5, with 0 being no risk and 5 being catastrophic risk.

Table 8-1. Risk Evaluation Scale

Risk	Rating
Catastrophic risk	5
Critical risk	4
Medium risk	3
Tolerable risk	2
Negligible risk	1
No risk	0

As the next step, each risk was assigned a probability of occurrence, and also the impact on the program if the risk did become a reality. Quantitative risk analysis comprised of multiplying the probability and the impact to arrive at a value associated with each risk.

The evaluated risks were collected into two categories: risk to the successful completion of the turbine development program; and risk related to the turbine performance once it went into operation to generate electricity. Impact calculations were based on:

- Costs, such as increased manufacturing cost
- Loss of customer earnings, such as lost revenue due to reduction in efficiency

All risks were then processed according to their probabilities and impacts to be categorized as High, Medium or Low risk. The categorization is based on preset criteria in the methodology that follows the guidelines from the standard IEC 61508 (International Electrotechnical Commission (IEC), *IEC 61508, Functional Safety of Electrical/Electronic/Programmable Electronicsafety-Related Systems*, Geneva, Switzerland, © 2005.)

8.1.3 Risk Mitigation:

Once the risks were categorized into high (catastrophic), medium (critical) and low (tolerable) categories, each risk falling under high or medium categories was considered for mitigation measures. Typically the mitigation measure would fall under one or more of the following scenarios:

- An alternate approach or product
- Upgraded (more robust) design or materials
- Testing of components under service simulated conditions
- Additional analysis before testing

8.2 Results

A systematic approach was applied to evaluate high level risks associated with the turbo machinery conceptual designs and interfaces with oxy-fuel combustors. This interface is considered to be one of several risk analyses required as design proceeds to the next level of details. Identification of a risk portfolio and mitigation measures helped to define the R&D effort needed to maximize success. Some of the high risk areas of development are as follows:

- Rotor thrust balance leakage
- Higher temperature thermal barrier coating (TBC) development
- Blade manufacturing involving modular design
- Blade R-1 design life
- Manufacturing of larger size vanes out of directionally solidified (DS) material
- Development of new cooling schemes
- Ceramic Matrix Composite (CMC) vane design life

Approximately 120 “topics” were identified as risks in the categories of system integration, IP turbine, HP turbine, combustor, and reheater. Due to the early nature of the program and preliminary nature of the re-heater design, quantitative evaluations of its risks were not possible, and topics associated with the re-heater were classified as uncertainties.

Of the 75 risks evaluated, 14 received qualitative evaluations. Risks with qualitative evaluations are listed in Tables 8-2 through 8-5 for evaluation levels 5, 4, 3, and 2.

Table 8-2. Catastrophic Risks (Qualitative Evaluation of 5)

Risk Area	Description	Level
R-34-4, Blades 1 - mechanical design– vibrations	Vibration risk for blade 1. This will be addressed in the detailed design	Low risk
R-17-2, Cooling medium - AUX boiler:	No alternative cooling medium available. For start-up an AUX boiler has to be used, but this is not complicated to design	Low risk
R-40, Ring Segment 2: Currently it is not clear how high the pressure loading for ring segment 2 is.	The risk is that the pressure loading is too high. Impact: CMC cannot be used and conventional metal design has to be used instead leading to more cooling steam is required (0.1%) and 0.025% less plant efficiency.	Low risk, around 1%
R-49, Static seals: Seal wires are foreseen on cover plates to rotor.	The seal wire seals the largest leak at the cover plates. The assembly of this kind of seals is difficult and a risk. The cover plate is	Low risk, around 1%

Risk Area	Description	Level
	segmented but the seal wire is one piece and an assembly procedure has to be developed to hold the pieces together. The risk is that the assembly will be made wrong and the flow consumption will go up. Impact: increase of leakage by 0.5% leading to 0.1% lower plant efficiency.	
R-27-5, R-29-5, R-50-5, Vanes 4, 5, and 6 manufacturing:	Manufacturing risk of the trailing edge of the airfoil. The risk is that the trailing edge has to be made thicker, Impact: loss of plant efficiency by 0.01%	Probability: 30%

Table 8-3. Critical Risks (Qualitative Evaluation of 4)

Risk Area	Description	Level
R-3, Cooling Steam Generator	: The cooling steam generator is a heat exchanger. Currently there is no difficulty seen in the design or control of the heat exchanger. Compared to the IPT, the HPT has much more time to react, if the cooling steam fails.	Low risk
R-54, Availability:	Smaller risk for the HPT because the IPT will need much more service time. If IPT needs to be open, service at the HPT can be made as well.	Low risk
R-60, Casing materials - Inner:	The larger the components that are casted, the less the material properties are uniform. The risk is that the material properties of the inner casing will be not good enough. More cooling steam will be required but currently there is enough potential margin.	Very low risk
R-55, Blade path design life:	Currently the blade path mechanicals were not being evaluated for 760°C but only for 750°C. Since the creep life will be 40% less for 760°C compared to 750°C there	Probability is high, around 60%

Risk Area	Description	Level
	is a large risk for not meeting the blade live requirements, Impact: only 150.000h blade path life will be reached, Probability: High No outage time assumed but \$100,000 cost for replacement of blades,	
R-38-2, Ring Segment 1 - material:	The ring segment will consist of multiple materials that are bonded together. The risk is, that the thermal stresses at the bond will be too large leading to break of the ring segment (worst-case: damage of downstream turbine parts). Before break cracks will occur and more cooling steam will be provided and cool the cracked parts ("self healing"). Damage of parts assumed to cost around \$1 Million.	Probability: very low

Table 8-4. Medium Risks (Qualitative Evaluation of 3)

Risk Area	Description	Level
R-66-3, Hot parts design life:	Risk for thermal mechanical fatigue due to extreme thermal gradients at certain parts of the combustor. Impact: Cracking occurs. Leakage of water into the combustion chamber. Parts break out of the combustion chamber and damage components downstream (valves, HP turbine). \$200,000 for damaged downstream components assumed.	Probability: very low

Table 8-5. Tolerable Risks (Qualitative Evaluation of 2)

Risk Area	Description	Level
R-44, Ring Segment 6-7		Low risk

Risk Area	Description	Level
R-51, Steam + CO2:	The steam reduces the oxidation resistance of CM247. To avoid the effects an internal coating is put on the components	Low risk
R-28, Vane 4 - new coating:	The risk is that the new coating will not work. Impact: vane life reduced from 24,000h to 12,000h 1 week outage for exchange + 1 week for re-start assumed	Probability: 5%

Post processing of the data indicated that:

- Risks associated with the development of the oxy-fuel turbines are higher than risks associated with its operation.
- The two highest risks by main component are the IPT and the combustor.
- The two highest risks by application field are Materials and Manufacturing.
- The two highest risks by technology category are CMC and airfoil manufacturing

The main mitigation measures are:

- Testing of components in rigs simulating the turbine conditions
- Additional materials testing to generate design data
- Rig testing of TBCs
- Consider redundancy in combustors
- Additional effort in resolving rotor thrust balance, fuel switchover from syngas to natural gas and changes in selected materials to facilitate design and manufacturing.

The results of the risk analysis are depicted in Figure 8-3.

Figure 8-3: Risks Associated with the IPT and Combustor

8.3 Conclusions

Currently this development program is at an early stage, and various new technologies have to be developed to fulfil the requirements. There are still many uncertainties that have to be clarified in order to get a clear picture of the risks. Most of the currently quantitatively evaluated risks are related to the IP turbine and the reheater.

Main risk drivers are the high turbine inlet temperature, high pressure, and the large dimensions of the airfoils requiring the development of new cooling schemes, TBCs, and other coatings, application of CMCs for vanes and ring segments, and manufacturing techniques for large directionally solidified airfoils.

The risk analysis exercise was successful in identifying risks, their impacts, and some of the mitigation steps under the current status of conceptual designs of the turbines. Risk analysis and monitoring will be a continuing process in this program and is expected to reach more detailed levels as the designs proceed.

The risk analysis exercise indicated the need for a significantly larger effort on rig testing to mitigate certain high risks. It also indicated a higher need to initiate the design effort of the re-heater and its integration with the high temperature IP turbine.

9.0 CONCLUSIONS

The original scope of the program involved three time-based classes of cycles:

- a “Baseline” cycle representing technology that could be commercial in 2006;
- a “Near Term” cycle representing technology that could be commercial in 2010; and
- a “Long Term” cycle representing technology that could be commercial in 2015.

However, funding limitations starting in 2007 changed the focus and objective of the project to a less complicated near term cycle that used a modified version of an existing gas turbine as its IP oxy-fuel expander.

The near-term IP turbine is a modified version of an existing gas turbine, but the subsequent near term and long term designs will include several technical challenges, such as:

- High inlet temperatures and pressures of the HP and IP turbines;
- Design software challenges related to the steam-CO₂ working fluid mixture;
- Operation and control challenges associated with near-stoichiometric combustion, transient, and by-pass operations; and new start-up ramp rates for new materials;
- Conceptual development of cooling circuits for casings, rotors, and blades;
- Development of CO₂-tolerant materials and valve coatings;
- Development of suppliers for newly developed material components;
- High-temperature designs of HP and IP rotors, casings, and valves, possibly made from dissimilar materials welded together; and
- Development of new high-temperature sealing materials.

The base metals, bond coats, thermal barrier coatings (TBCs), and rotor materials used in the SGT-900 were tested for their ability to operate in the steam- CO₂ environment of the oxy-fuel OFT-900. Testing included corrosion, low-cycle fatigue (LCF), tensile, and crack growth evaluations. Test results indicated that these same materials would operate satisfactorily in the OFT-900, although with slightly reduced service lives. The plan for the OFT-900, therefore, is to use the same materials that were used in the SGT-900.

Follow-on programs for corrosion testing to 3,000 hours in oxy-fuel environment and evaluation of the crack growth rate of Blade 1 and 2 alloy IN738 in environment have been proposed. These follow-on programs will build on the results presented here and provide a more conclusive and quantifiable assessments of the effects of oxy-fuel environments on the service lives of turbine components.

An economic analysis and market demand study for oxy-fuel turbine cycle performed by Science Applications International Corp. (SAIC) indicated that oxy-fuel turbine cycles start to look attractive in 2025 when the CO₂ tax is assumed to reach \$40/ ton, and by 2030 it has a clear advantage over both IGCC with sequestration and pulverized coal with sequestration.

A risk analysis workshop conducted by Siemens Corporate Technology identified the relative risks of this program. The analysis included the oxy-fuel combustor, HP turbine,

re-heater, and IP turbine of the far term cycle, but not other parts of the plant, such as the gasification island.

Risks were identified and categorized into high (catastrophic), medium (critical) and low (tolerable) categories, and each risk falling under high or medium categories was considered for mitigation measures, such as:

- Testing of components in rigs simulating the turbine conditions
- Additional materials testing to generate design data
- Rig testing of TBCs
- Consider redundancy in combustors
- Additional effort in resolving rotor thrust balance, fuel switchover from syngas to natural gas and changes in selected materials to facilitate design and manufacturing.

These mitigation steps will help the conceptual designs of the turbines and the ultimate success of the program.

10.0 LIST OF ACRONYMS AND ABBREVIATIONS

AEO	DOE-EIA Annual Energy Outlook
AEO2007	DOE/EIA Annual Energy Outlook, 2007
AGR	Acid Gas Removal
APEP	Advanced Power and Energy Program of the University of California
CCS	Carbon capture and sequestration
CES	Clean Energy Systems, Inc. of Rancho Cordova, California
CMC	Ceramic Matrix Composite
COE	Cost of Electricity
DOE	U.S. Department of Energy
DS	Directionally Solidified
EBC	Environmental Barrier Coating
ECP	Electricity Capacity Planning Sub-module of NEMS
EIA	USDOE Energy Information Administration
EMM	Electricity Market Module, the Major Link to the NEMS Modeling Framework.
EPACT05	Energy Policy Act of 2005
FGD	Flue Gas Desulfurization, Desulfurizer
FTT	Florida Turbine Technologies, Inc.
GW	Gigawatt = 1,000 megawatts
HHV	Higher Heating Value
HRSG	Heat Recovery Steam Generator
IGCC	Integrated Gasification Combined Cycle
IGCC/S	IGCC with Sequestration
ITC	Investment tax credit
LCF	Low Cycle Fatigue
LCOE	Levelized Cost of Electricity at the Busbar
NASA	National Aeronautics and Space Administration
NEMS	National Energy Modeling System
NERC	North American Electric Reliability Corporation
NGCC	Natural Gas Combined Cycle
NGCC/S	Natural Gas Combined Cycle with Sequestration
NGOC	Natural Gas Oxy-Fuel Turbine Cycle
O&M	Operation and Maintenance

ODS	Oxide-Dispersion Strengthened
OFT	Oxy-Fuel Turbine
OFTC	Oxy-fuel Turbine Cycle
ORNL	Oak Ridge National Laboratory
PC	Pulverized coal
PCS, PC/S	Pulverized Coal Plant with Sequestration
SAIC	Science Applications International Corporation
SC	SiCoat (Siemens coating)
SGT	Siemens Gas Turbine
SI	Système Internationale Units (kg, m, °C, etc.)
SX	Single Crystal
TBC	Thermal Barrier Coating
US	United States, or US Customary Units (lb, ft, °F, etc.)
WBS	Work Breakdown Structure
WOP	World Oil Price
ZEPP	Zero Emission Power Plant

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APPENDIX I – JULY 2008 WHITE PAPER

White Paper

**Siemens Power Generation and Clean Energy Systems, Inc. Proposal for
the Future Scope of Turbine Development and Combustor Development for
Oxy-Fuel Cycle**

**Awards DE-FC26-05NT- 42646 and
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**Submitted to DOE-NETL
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Executive Summary

This *White Paper* presents the joint position of Siemens Power Generation and Clean Energy Systems (CES) for the scope of the oxy-fuel turbine development program for the next 4 years. As Phase I of the Siemens program comes to a close (and year 1 of Phase II for CES draws to a close), Siemens and CES would like to propose to DOE-NETL an approach that makes possible an early demonstration of power generation (>200MWe) with CO₂ capture that minimizes turbine development effort. The proposed approach capitalizes on the achievements of Phase I, maintains the need to validate design concepts that are key to power generation with zero CO₂ emission and adjusts the program to the current realities of budgetary constraints.

The program goal is the commercial deployment of second generation, oxy-fuel power plants that capture and sequester >99% of the produced CO₂, at a competitive cycle efficiency and cost-of-electricity, using natural gas or coal-derived syngas as fuel. This will require the development of two key components, namely an intermediate pressure turbine and a reheater, and testing of these components. To accomplish the development, we propose this modified program which builds on the existing CES development efforts and the existing NETL-funded projects. The restructured program will serve as a bridge to “third generation” plants that meet the goals of the NETL projects awarded to CES and Siemens (DE-FC26-05NT42645/6). Funding for the third generation technology development will not be solicited until the second generation technology is demonstrated.

The position advocated in this *White Paper*, if accepted by DOE-NETL, would lead to design modification work on the Siemens SGT-900 gas turbine, selection of Siemens steam turbines and their design modifications, design of CES combustor and reheater needed to work with the turbines and the related cycle optimization studies. It would make it possible to ship a modified SGT-900 turbine in 3 years to a zero emissions power plant (ZEPP). This will allow testing of the higher temperature SGT-900 in a simple cycle for a year, to be followed later by operation as an integrated base load plant.

Both Siemens and CES realize that, in order for zero CO₂ oxy-fuel power generation to gain general acceptance, a business case needs to be demonstrated that will take into account the capital costs of a ZEPP, its operational costs and the anticipated business climate of a carbon cap and trade system. We believe the program proposed here provides this opportunity to be realized in a time frame that is shorter than continuing on the scope of the original Phase II for Siemens. Further, it is an essential step towards achieving larger, more complex and technically much more challenging goal of very high temperature turbines with higher operating efficiencies.

Included in this document in addition to the background and status information are: (a) the proposed scope for FY09-FY12 period, (b) key milestones (c) the benefits to DOE-NETL, and (d) requested future steps. An estimate of the needed funding is also provided.

Introduction and Background

Since October 2005 Siemens Power Generation, Inc. (SPG) and Clean Energy Systems, Inc. (CES) have been engaged in the development of combustors and turbo machinery for zero CO₂ emission coal syngas-oxygen cycles. Significant steps have been taken

and important deliverables accomplished over the last 33 months towards meeting the goals set by DOE-NETL in the award. The following is a list of achievements to date:

Siemens:

- Completion of the Research & Development Implementation (RDI) plan
- Cycle modeling completed for near term and far term cycles including the turbine configuration as “direct” or “indirect”
- Completed conceptual designs of turbines for the baseline, near term and far term cycles
- Recommendation to DOE-NETL of far term cycle because of achievable time line and higher efficiency
- Completion of high level risk analysis – risk portfolio and mitigation measures identified
- Completion of a comprehensive economic analysis of oxy-syngas and oxy-natural gas power generation which indicated highly favorable positioning of this type of power generation under a carbon tax environment
- Successful presentation and defense of the program in front of the Advanced Power Systems peer review panel in July 2007

CES:

- Completion of the Research & Development Implementation (RDI) plan
- Definition of oxy-syngas cycle concepts for near-term and far-term applications. Modeling results were provided to UC-Irvine (APEP) for final systems analyses using AspenPlus.
- Successful demonstration of CES’s 4-inch diameter combustor on simulated syngas and hydrogen-depleted syngas at power levels of up to 5 MWth
- Completed detailed design of a 12-inch diameter (100 MWth) syngas combustor
- Conceptual design of a syngas reheat combustor
- Successful presentation and defense of the program in front of the Advanced Power Systems peer review panel in July 2007

Current Status

Siemens

Since the beginning of FY08, a program re-focus, compatible with available funds, was sought and agreed to with DOE-NETL. The program took a nearer term perspective and it was aligned to closely support a potential oxy-fuel turbine power generation demonstration project in the 2012 -13 time period while still maintaining a link to the requirements of the far-term oxy-syngas cycle. Briefly, the current tasks include:

- 3D computational fluid dynamics (CFD) based turbine heat transfer methodology
- Modular components for high heat flux applications
- Oxidation characterization of SGT-900 turbine material systems in steam/ CO₂ environment
- Test matrix to determine mechanical properties of SGT-900 turbine alloys in steam/ CO₂ environment
- Direct metal fabrication (DMF) method evaluation for advanced modular components

The SGT-900 turbine has been identified by Siemens as the best fit intermediate pressure turbine (IPT) for a ZEPP cycle proposed by CES for implementation in the 2012-13 time frame. Although the initial fuel consideration for this cycle is natural gas, the focus on turbo machinery that works on steam/ CO₂ drive gas also allows conversion of the turbines to work with coal syngas. By the end of September 2008, Siemens will have completed the following steps towards incorporating a SGT-900 turbine in a near term ZEPP:

- Identification of critical failure mode(s) of materials of the components in the hot gas path
- Generation of required materials testing matrix to understand expected life of components
- Completion of environmental exposure tests on super alloys and coatings of the blades and vanes

Clean Energy Systems:

During this period, CES refocused their Phase II program on reheat combustor development, and specific long-lead engineering tasks that support the SGT-900 conversion. Collaborating with Florida Turbine Technologies, Inc. (FTT), CES assessed the feasibility of modifying an existing combustor can from a J79 turbine to serve as an oxy-fuel reheater. Once modified, the J79 reheater will be tested at CES's Kimberlina plant by reheating steam/ CO₂ generated in the existing 20 MWth combustor. Delivery of the reheater is expected in late September 2008, with testing to follow in October. In a parallel task, the team will perform a detailed design of a modified SGT-900 reheater. CES has also completed the following work scope at FTT:

- CES funded feasibility study of operating a modified SGT-900 gas turbine expander in a CES oxy-fuel cycle with steam/ CO₂ as the working fluid
- Evaluation of the above turbine for performance, expected operating characteristics, required modifications and prediction of the internal secondary flow system

Phase II Goals and Scope (FY09 to FY12)

Siemens and CES believe that these studies and test results described above, along with the recently announced DOE award to WESTCARB partnership [Ref 1] provide a solid platform to launch future effort starting in FY09 as described below.

Overall Goals:

The program objective is the design development and testing of second generation, oxy-fuel power plants that capture and sequester >99% of the produced CO₂, at a competitive cycle efficiency and cost-of-electricity, using natural gas or coal-derived syngas as fuel. This will require the development of two key components, namely an intermediate pressure (IP) turbine (SGT-900) and a reheater, and testing of these components as a modified SGT-900 "simple-cycle oxy-fuel" IP turbine.

To accomplish these tasks, we propose this modified program leading to construction and test of the two components, building upon the existing CES development efforts, modifying an existing Siemens turbine design, and the existing NETL-funded projects. This restructured program will serve as a bridge to "third generation" plants that meet the goals of the NETL projects awarded to CES and Siemens (DE-FC26-05NT42645/6). Funding for the third generation technology development will not be solicited until the second generation technology is demonstrated.

Siemens and CES envision the Phase II of the program as (a) engineering development to adapt an existing Siemens turbine to steam/ CO₂ drive gas and to integrate it with CES oxy-fuel combustors and re-heaters, (b) a test bed for oxy-fuel turbine performance prediction and materials life, (c) a vehicle to verify the economics of oxy-fuel power generation under a carbon-constrained national policy; and (d) an intermediate step towards utilizing coal syngas as the fuel source in a zero CO₂ emission power plant.

(For a description of the first generation and second generation zero CO₂ emissions plant, please see Appendix A)

Benefits to DOE-NETL and Adherence to the Original Program Goal

Siemens and CES recognize that the overall goal (2005-2015) of the *Turbine Program* within NETL is to provide high efficiency, near zero emissions and lower cost turbines for coal-based stationary power systems [Ref 2]. In specific, the funding opportunity objectives for Phase II is stated as “ *The objective of Phase II efforts is to develop a detailed design and conduct validation testing to allow a proof-of-concept prototype to be designed, built and tested in Phase III.*”

The objective and main tasks suggested here by Siemens and CES allow DOE-NETL to maintain the goal of the original solicitation by allowing an early intermediate step that demonstrates proof-of-concept at a far reduced cost. The following benefits are seen in the approach proposed:

1. **Opportunity for early demonstration:** If the program continues on the original path pursuing the far term cycle (1760⁰C inlet conditions for the IP turbine), Phase II would be expected to take 4 to 7 years. After Phase II, the manufacture of turbines and testing (Phase III) might require a comparable schedule, pushing the target for achieving NETL goal well beyond the 2015 time frame. With the approach proposed here, incorporating the turbines into a zero emission power plant, generating power and capturing CO₂ could happen as early as 2012.
2. **Budget savings:** Phase II of the original Siemens program could need a budget exceeding \$75 million. The design and manufacturing support effort proposed here to modify existing turbines for steam/ CO₂ use is expected to be considerably less expensive – approximately \$11M (DOE plus SPG and CES) million. In addition, an appropriate test facility could likely be furnished at a cost less than the earlier anticipated Phase II development cost of \$75 million.
3. **Development of design tools:** The design tools needed to establish the performance and life of steam/ CO₂ operated turbines will have been developed and applied, albeit, at temperatures lower than those for the far-term oxy-syngas cycle. The Phase III testing will provide an opportunity to validate the design calculations and performance predictions.
4. **Understanding of Materials Behavior:** The deployment of the turbines in a power generation cycle will provide ample opportunities to understand the behavior of super alloys and coatings in the hot gas path regardless of the temperature range. Even though the substrate materials in the SGT-900 IP turbine will need upgrades if used in a higher temperature turbine for the far term cycle, life prediction models under the operational conditions of this new drive gas can be tested. Post operational tests on materials will provide valuable data on remaining life that would help determine the frequency of inspection.
5. **Opportunity to switch over to coal syngas:** The second generation ZEPP will lack a coal gasifier in the beginning since the fuel is likely to be natural gas. But, an opportunity exists to add a gasifier at a later stage and convert the plant to run on coal syngas. The air separation unit (ASU) is expected to be incorporated in the original plant design to provide the needed oxygen for oxy-combustion of natural gas.

Timeline of Main Tasks and Deliverables

The main tasks and their timelines are as shown in the diagram below. The diagram also shows some key deliverables for hardware and software. A brief description of the main tasks is given in the following section.

		FY09				FY10				FY11				FY12			
		Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
1	First generation reheater development																
2	Materials compatibility in steam/CO2																
3	Second generation reheater development																
4	SGT-900 design adaptation to oxy-fuel conditions																
5	Design reviews and materials ordering			G-R3		G-R5		S-R3		S-R5							
6	HPT and LPT selection & performance study																
7	BOP (condenser, pumps etc.) study																
8	SGT-900 disassembly & modification																
9	SGT-900 shipment, installation and testing																
	Deliverables																

Notes:

G-R3 = preliminary design review and long lead materials ordering for SGT-900

G-R5 = detailed design review and release for modification for SGT-900

S-R3 = preliminary design review and long lead materials ordering for HPT, LPT

S-R5 = detailed design review and release for modification for HPT, LPT

D-1 = Shipment of SGT-900 to site

D-2 = Installation complete, start of testing

Brief Descriptions of the Main Tasks

A. Design and analysis related:

1. First generation reheater development: CES will modify all ten J79 combustors to serve as reheaters, and install them in the modified J79 turbine at Kimberlina. A CES developed 20 MW_{th} combustor will be fired on natural gas to produce the required quantity of steam/CO₂, which will be reheated to temperatures of 927°C (1700°F) from 316 °C (600 °F) by burning additional natural gas with oxygen.
2. Materials compatibility in steam/ CO₂ fluid: Since the materials in all turbines (HP, IP and LP) for the ZEPP 2 plant will be used in steam/ CO₂ drive gas for the first time, very little is known about the ability of these materials to withstand the turbine conditions. Initial exposure tests under laboratory tests on SGT-900 blade path materials were started in June 2008. While the results will be useful in ranking the materials compatibility, more advance testing will be required to generate some life assessment predictions. This work package will seek to accumulate materials and coatings life data that simulates turbine conditions as far as possible.
3. Second generation reheater development: CES, FTT, and Siemens will design and fabricate a second generation reheater, based on the design of the existing SGT-900 combustor, drawing upon results from the first generation J79 tests. This SGT-900 reheater will be tested at Kimberlina using steam/CO₂ gas from the previously established 170 MW_{th} combustor. Initially it will reheat the steam/CO₂ from 316 °C (600 °F) to 1080 °C (1976 °F) and later to the design value of 1180 °C (2156 °F).
4. SGT-900 design adaptation to oxy-fuel combustion conditions: CES, FTT, and Siemens will perform a detailed engineering analysis and produce a design of a modified SGT-900 turbine that is suitable to run as an oxy-fuel turbine in steam/ CO₂ drive gas. In this task, this design will be captured in a set of manufacturing drawings.
5. Design reviews and materials ordering: This task will plan and execute the required steps for passing the modified design of the turbines by a controlled design review process. Reviews will be timed so as to allow the ordering of long lead materials, release of manufacturing drawings and release for shipment to test site.
6. High pressure and low pressure turbines selection and performance study: While the manufacturing and shipment of the HP and LP turbines is not included in the proposed scope, all first-time engineering analysis will be completed including necessary design reviews to release of the turbines for manufacturing.
7. Balance of plant equipment study: This task includes the typical scope of supply for Siemens as the OEM of the turbines. As such it includes interface with the A/E for specifications of equipment such as the condenser, compressors, pumps, HRSG etc.

B. Hardware manufacturing related:

8. SGT-900 disassembly and modification: The purchased SGT-900 turbine will be disassembled to the extent required, inspected and prepared for refurbishment as the results of Task 4 above. A preliminary scope of the required modifications has already been identified by the CES/FTT/Siemens team.

C. Site testing related:

9. SGT-900 shipment, installation and testing: The modified turbine will be available for commissioning and demonstration at a test facility constructed for the purpose, possibly involving incorporation into an operational peaking plant. One potential location is a

Deep Water Terminal plant, which may be built at Pasadena TX. Alternative locations are possible. A fixed location need not be firmly decided at this stage.

Funding Needs:

The table below provides a top level estimate of the funds needed during FY09 – FY12 period to perform the tasks described above. The split between Siemens and CES is approximate. FTT effort is shown in CES column. The figures shown include DOE and contractors' cost share.

Task	CES Funding Need	Siemens Funding Need	Simple Cycle Oxy-fuel Test Plant
First generation reheater development	\$1.4M	--	--
Materials compatibility in steam/ CO ₂	--	\$1.4M	--
Second generation reheater development	\$0.7M	--	--
SGT-900 design adaptation	\$2.5M	\$2.7M	--
Design reviews and long lead material ordering	--	\$0.5M	--
HPT and LPT selection and performance study	--	\$1.2M	--
Balance of plant study	--	\$0.8M	--
SGT-900 procurement, disassembly and modification incl. reheaters	--	--	\$14.0M
SGT-900 shipment, installation and testing***	--	--	\$57.8M
Approximate Total	\$4.6M	\$6.6M	\$71.8M

*** includes cost of equipment such as generator, gearbox, HRSG, FWH, pumps, oxygen equipment etc. plus site construction & contingency

Upon the receipt of further guidance from DOE-NETL, Siemens and CES will provide more details of the cost estimates.

Next Steps

We request that DOE-NETL take the following steps:

1. Comments/feedback on the proposed plan
2. NETL to direct Siemens and CES to prepare a Continuation Application for Phase II with scope as presented here and provide funding guidelines for out years
3. NETL/Siemens/CES meeting to discuss the proposed effort in details and sort of the division of responsibility for scope of supply

4. Siemens and CES to submit the Continuing Application 60 days after receipt of DOE guidance

Concluding Remarks

On the basis of the progress made to date and in consideration of the funding reality of the near future, Siemens and CES have jointly proposed a program for Phase II of the Siemens award (and continuing effort for CES's current phase). This program, while deviating slightly from the original intent of the award, still maintains the principles of technology demonstration and feasibility that the original program aimed to attain. The proposed program brings to fruition important technological achievements closer in time frame and allows DOE-NETL to achieve the goal of demonstrating CO₂ capture while generating 200 MW power in the near term. It also allows a platform from where NETL can reach for more ambitious goals of increased efficiencies and fuel flexibility once the zero emissions plant is commissioned.

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2. Funding opportunity announcement DE-PS26-05NT42380 "Enabling Turbine Technologies for High Hydrogen Fuels" dated March 31, 2005, Part I, page 7.
3. Hebbar M.A. (Siemens Power Generation, Inc.), Zero Emissions Coal Syngas Oxygen Turbo Machinery (Cooperative agreement number DE-FC26-05NT42646) Quarterly Progress Report for FY07 Q2 dated April 18, 2007 submitted to US DOE-NETL.

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Anderson, R., F. Viteri, R. Hollis; M. Hebbar; J. Downs, D. Davies, and M. Harris, "Application of Existing Turbomachinery for Zero-Emissions Oxy-Fuel Power Systems," ASME paper GT2009-59995, presented at TurboExpo 2009: Power for Land, Sea and Air, Orlando Florida, June 8-12, 2009. (peer-reviewed)

Siemens Power Generation and Clean Energy Systems, Inc. Proposal for the Future Scope of Turbine Development and Combustor Development for Oxy-Fuel Cycle, Awards DE-FC26-05NT- 42646 and DE-FC26-05NT- 42645, white paper submitted to DOE-NETL, July 29, 2008.

APPENDIX –A

Explanation and Simplified Schematic of an Oxy-Combustion System Concept

Clean Energy Systems, Inc. (CES) has developed a near zero-emission power generation technology by integrating proven aerospace technology into conventional power systems. A simplified schematic of the process is shown in Figure 1. The core of the CES process is a high-pressure oxy-combustor, which burns fuels such as natural gas or syngas from coal, biomass, petcoke, etc. with oxygen in the presence of water to produce a steam/CO₂ mixture at high temperature and pressure. This stream is used as working fluid to drive a high-pressure steam turbine (HPT), while the HPT exhaust is reheated, by burning additional fuel with oxygen in a reheater combustor, to produce working fluid for a modified gas turbine expander, or intermediate pressure turbine (IPT). In the configuration shown in Figure 1, the IPT exhaust enters a condensing HRSG (heat recovery steam generator) to create pure low-pressure steam to drive a low-pressure turbine (LPT). The HRSG also serves to separate water from CO₂. The water is recycled to the combustor, while the recovered CO₂ is conditioned and purified as appropriate and sold or sequestered. A plan has been developed in this joint White Paper, which describes the activities required to develop, build and test three key components of the cycle:

- (i) The first generation reheat combustor or “reheater”
- (ii) The second generation reheat combustor. and
- (iii) The high temperature Intermediate Pressure Turbine (IPT),

Figure 1. Conceptual layout of CES oxy-fuel cycle

Systems studies have shown that the performance of the CES oxy-fuel cycle is greatly enhanced by increasing the inlet temperature of the IPT. Although gas turbines with high inlet temperatures are readily available, the resources required to adapt these machines to the CES working fluid are relatively significant. Because of this, CES has elected to develop and commercialize their oxy-fuel technology in stages, with each

stage or generation linked to a specific IPT with a progressively higher inlet temperature. In this fashion, CES has defined the technology "generations" described below.

First Generation oxy-fuel plants are early deployment plants that use commercially available power plant components and equipment that is easily modified. To facilitate early deployment and demonstration, these plants will be in the ~50 MW_e size range and will be located where a revenue stream can be generated from the CO₂ by-product. Locations will likely be near oil or gas producing areas where the CO₂ can be used for enhanced oil recovery (EOR) or enhanced gas recovery (EGR). The plants will use a modified GE J79 turbine that CES has been adapting for their steam/CO₂ working fluid. CES plans to test the modified J79 turbine at its Kimberlina Power Plant (KPP) in the fall of 2008 using steam/CO₂ working fluid from a 170 MW_{th} natural gas-fired combustor. In these tests, the gas will be conveyed to the modified turbine at temperatures of up to 760°C (1400°F) via a specially designed Inconel 600 volute (manifold). With successful demonstration of a modified J79 combustor used as a reheater, the volute will be moved upstream to the compressor rear support frame where the incoming steam/CO₂ gas temperature will be at approximately 316 °C (600 °F). These cool steam/CO₂ gases will be reheated to 927 °C (1700 °F) using the 10 modified J79 combustor cans to drive the J79 three stage turbine. The 927 °C (1700 °F) temperature is the original design temperature of the J79 gas turbine.

Second Generation plants will use a modified IPT with a significantly higher inlet temperature of up to 1180°C (2156°F) to 1260 °C (2300 °F) . The selected turbine is the Siemens SGT-900 (formerly Westinghouse W251B) gas turbine, which Florida Turbine Technologies (FTT) has evaluated under contract to CES. Siemens has supported the effort of FTT by provision of original hardware drawings, identification of materials employed, and comment on FTT draft materials. The SGT 900 modification plan has been studied by FTT and is declared feasible. The higher power level of the machine will increase the plant output from ~50 MW_e to 150-200 MW_e. The higher IPT inlet temperature and pressure will increase the overall cycle efficiency, while the economy of scale benefits from the larger plant will lower capex, particularly for coal applications that require a gasifier. The expected cycle efficiency of these plants is 37- 43 % (LHV) on natural gas and 30-36 % (HHV) on coal-derived syngas, with >99% CO₂ capture. These net plant efficiencies include all the parasitic loads of the required air separation unit (ASU), the CO₂ compression system, and other auxiliary loads.

The plan in the joint White Paper describes reheater development tasks being executed under CES's current DOE/NETL project, as well as new proposed tasks (including test hardware fabrication and testing) that will ultimately lead to the commercial deployment of second generation reheaters and IP turbines in zero-emissions power plants.

Reference:

R. E. Anderson, S. MacAdam, F. Viteri, D. O. Davies, J. P. Downs, and A. Paliszewski, "Adapting Gas Turbines to Zero Emission Oxy-Fuel Power Plants," a paper presented at Turbo-Expo 2008, Berlin, Germany, ASME Doc. No. GT2008-51377, to appear in the conference Proceedings. Also available at <http://www.cleanenergysystems.com/> Touch "Technology" and "Technical Papers."

White Paper

Siemens Power Generation (SPG) and Clean Energy
Systems (CES) Position on Long Term Possibilities for
Efficiency Improvement of Power Plants Based on Oxy-Fuel
Combustion and 100% Capture of Carbon-Dioxide

Submitted to DOE-NETL
June 12, 2006

Prepared by Clean Energy Systems, Inc. and
Siemens Power Generation, Inc.

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DE-FC26-05NT42645 and
DE-FC26-05NT42646

Siemens Power Generation (SPG) and Clean Energy Systems (CES) Position On Long Term Possibilities for Efficiency Improvement of Power Plants Based on Oxy-Fuel Combustion and 100% Capture of Carbon-Dioxide

Executive Summary

In response to a recent request from DOE-NETL, Clean Energy Systems, Inc. (CES) and Siemens Power Generation Inc. (SPG) have jointly prepared a White Paper which incorporates the results of modeling the efficiency of a zero emissions oxy-fuel combustion power plant. Since the combustor, turbo machinery and the auxiliary equipment can be configured in a variety of ways giving rise to numerous interfaces, the assumptions made regarding the performance of each equipment have an influence on the overall plant efficiency. While a few boundary conditions used in this analysis still need to be verified with auxiliary equipment suppliers, both CES and SPG have tried to use reasonable assumptions in modeling. The assumptions have been applied to the near term cycle (~2010) and the long term cycle (~2015) depending on the expected time frame for realization of a technological advancement affecting the plant cycle.

Modeling indicates that a 30% efficiency is possible for the near term cycle¹. For the long term cycle, with the incorporation of additional technology breakthroughs, it is possible to reach an efficiency of approx. 39% as suggested by the modeling analysis. The paper also lists further areas of developments that are capable of improving the efficiency beyond the 2015 time frame in order to reach the DOE goal of 50%. These improvements may, collectively add approximately 4% points to the cycle efficiency, thereby boosting the long term (>2015) cycle efficiency to approx. 43%.

A graphical rendering of the efficiency as a function of technology implementation is shown in the figure below.

¹ All references to efficiency are coal-to-grid, HHV, with CO₂ delivered at sequestration pressure of 152 bar.

Coal-to-Grid Oxy-Fuel Combustion Power Plant Efficiency with CO₂ Capture (HHV Basis)

Introduction and Background

CES and SPG are involved in the study and development of combustion technology and turbo machinery, respectively to utilize coal-derived fuels to generate power with nearly zero emissions, complete capture of CO₂ and high efficiency. The efficiency goal set out by DOE-NETL for the long term (~2015) is 50% to 60%, coal-to-electricity on HHV basis. This goal has been the target for the two programs (DE-FC26-05NT42645 for CES and DE-FC26-05NT42646 for SPG) that were initiated in October 2005.

In the cycle selection tasks of these programs, CES has the lead role in cycle selection and modeling, while SPG's role is to evaluate the effect of the cycle conditions on the turbo machinery and to provide feedback to CES on realistic conditions attainable in the high temperature gas turbine and in various elements of the steam turbines.

The results of cycle analysis are dependent on the assumptions made about key components in power plant. These components include the gasifier, the air separation unit, compressors, and heat exchange equipment as well as the combustor and turbines. The design of some of these components are under the control of SPG and CES, while the equipment considered 'auxiliaries' is developed and supplied by outside vendors.

Cycle Selection

CES has proposed various cycles for coal-based zero emission power plants. The most promising of these have been modeled by CES using the AspenPlus 2004.1 process simulation tool. Based on the simulation results, CES and SPG are in agreement that a near term cycle as shown in **Figure 1** may offer the best practical efficiency for the time frame 2010 and a long term cycle as shown in **Figure 2** may offer the best practical efficiency for the time frame 2015.

Figure 1: Near Term (~2010) Zero Emissions Oxy-Fuel Combustion Power Plant Cycle

Figure 2: Long Term (~2015) Zero Emissions Oxy-Fuel Combustion Power Plant Cycle

There are two key differences between the cycles shown in Fig. 1 and Fig. 2. Firstly, the long term cycle takes advantage of developing materials technology to enable the operation of the turbo machinery at much higher temperatures than possible in the near term. Secondly, a high pressure combustor is added to the front end of the cycle to enable additional work from a steam/CO₂ high pressure turbine. This steam/CO₂ high pressure turbine is considered a long term development due to uncertainties of the effect of the working fluid on materials of construction. In addition, design tools will have to be developed and validated to fully understand the thermodynamic performance of the HP turbine with a steam/CO₂ working fluid.

In both cycles, steam is provided to the high-temperature intermediate pressure turbine (IPT) to serve the cooling requirements of the turbines. This cooling steam is generated in the syngas cooler and in the HRSG, depending on the pressure and temperature requirements of the steam. In each cycle, the cooling steam is assumed to follow an open-loop path through the turbine, which results in the steam being admitted into the steam/CO₂ working fluid.

Efficiency of the Near Term Cycle

In order for the near term cycle to be offered commercially around the year 2010, the final designs of the combustor and turbo machinery would need to be completed in accordance with the business processes and quality assurance requirements of SPG and CES. For the SPG turbo machinery, this will require that proven designs of gas turbines and steam turbines be offered with a limited leap in technology. SPG has applied this limited leap in 2 areas – (i) in extending the steam turbine technology from 593 deg C inlet steam condition to 620 deg C inlet steam condition, and (ii) applying gas turbine technology to the high temperature IP turbine where the working fluid is novel, consisting of a mixture of steam and CO₂. These advancements are deemed to be appropriate for the 4-5 year time frame.

For the auxiliary equipment capabilities, both CES and SPG have relied on currently available and *credible* information obtained from the equipment suppliers. Both companies have tried to avoid the use of unverifiable performance numbers in drawing up the assumptions for modeling the cycle. The assumptions made in the modeling of the near term cycle are shown in **Table 1**. CES and SPG are still trying to verify the validity of certain assumptions shown in this table which are listed in **Appendix 1 and Appendix 2**.

The coal-to-grid (HHV) efficiency of the near term cycle, based on the assumptions in Table 1 and subject to the verification listed in the appendices is **30.0%**.

Table 1: Assumptions made for near term cycle modeling

No.	Assumption or Auxiliary Equipment Information	Value or Feature Used in Modeling	Basis/Justification
1	Gasifier type	Full Slurry Quench	<ul style="list-style-type: none"> • Provided by COP (ConocoPhillips)
2	Syngas conditions at the outlet of the gasifier island (temperature, pressure)	27.6 bar, 177°C, and 20% moisture	<ul style="list-style-type: none"> • Provided by COP (See List of References) • Subject to Appendix 1
3	Gasifier cold gas efficiency	80.32%	<ul style="list-style-type: none"> • Provided by COP (See List of References)
4	Stream interfaces with the power block	0.2472 kg of LP steam (at 3.5 bar, 203°C) and 0.0851 kg of Hot BFW (at 111 bar and 293°C) required per kg dry syngas	<ul style="list-style-type: none"> • Provided by COP (See List of References) • Subject to Appendix 1
5	Syngas cooler duty	1.4773 MW per kg dry syngas	<ul style="list-style-type: none"> • Provided by COP (See List of References)
6	Gasifier condensate heater duty	0.4773 MW per kg dry syngas	<ul style="list-style-type: none"> • Provided by COP (See List of References)
7	Air Separation Unit (ASU) auxiliary load	0.200 kWh/kg O ₂	<ul style="list-style-type: none"> • Reference 1 (See List of References)
8	CO ₂ compressor efficiency	80 %	<ul style="list-style-type: none"> • Subject to Appendix 2
9	O ₂ compressor efficiency	85 %	<ul style="list-style-type: none"> • Subject to Appendix 2
10	Gasifier auxiliary load	0.138 kWh/kg syngas	<ul style="list-style-type: none"> • Based on ASU and O₂ compressor assumptions (above) plus information from COP • Subject to Appendix 1
11	IP steam/CO ₂ turbine inlet conditions	1450°C and 30 bar	Provided by SPG
12	IP steam/CO ₂ turbine outlet pressure	1 bar	Provided by SPG
13	Cooling demand for IP turbine components	Turbine cooling & leakage coolant (TCLC) at 25% of inlet flow.	Near term only allows transfer of current gas turbine technology to a steam/CO ₂ 'gas' turbine.
14	Cooling loop for IP turbine blade path	Open loop steam cooling only	Close loop steam cooling is unproven in Siemens gas turbines.

Cycle efficiency (HHV, coal-to-grid) = 30.0%

Efficiency of the Long Term Cycle

The long term cycle takes advantage of emerging technologies currently being pursued by various equipment providers. Some of these technologies are still in their pre-commercial development stages, but targeted to be developed by the year 2015, which is the long term timeline for the CES and SPG technologies.

Unlike the near term cycle, where all technologies were assumed to be available at one time and incorporated in one case, CES & SPG have chosen to evaluate the long term cycle in a series of cases, incorporating one emerging technology after another in a sequential manner. This approach provides a clear picture of the impact of an individual assumption or technology on the overall plant cycle efficiency.

The list of the assumptions for the long term cycle is shown in **Table 2**. It is important to mention here that while these are still considered 'emerging' or under development, CES and SPG have selected the features only after a careful scrutiny of the on-going developments supported by either private or public funds. While the potential of these technologies have been taken from publicly available information, neither SPG nor CES makes claims about the successful conclusion of these programs in time to incorporate them in the long term cycle. CES and SPG have chosen to evaluate the *importance* of these peripheral developments on the efficiency of the oxy-fuel cycle to provide DOE-NETL with important information regarding decisions on future funding.

The *order* shown in Table 2 is also important and is arranged based on the confidence level and familiarity with the said technology. For this reason, the first four items apply to technologies that are within the control of CES and SPG.

Table 2 lists the additional cases that were included in the long-term cycle modeling effort. A brief explanation of each case is as follows:

Case 1 indicates the same auxiliaries used in the near term cycle but adds the planned developments in the HP combustor and the HP steam/CO₂ turbine. The IP turbine cooling & leakage coolant (TCLC) flow is assumed to be 25% of IPT inlet flow, which is the same assumption made for the near-term (2010) case.

Case 2 indicates the same conditions as Case 1 but with a IP turbine cooling & leakage coolant (TCLC) flow equivalent to 15% of the inlet flow. This reduction would be achieved by advances in steam cooling technology and in materials.

Case 3 represents the benefits to the cycle efficiency from using the advanced ITM (Ionic Transport Membrane) oxygen production technology under development by Air Products.

Cases 4 represents the benefits of advancements in CO₂ compression technology.

Table 2: Assumptions made for long term cycle modeling

Case Number for Modeling	Assumption or Auxiliary Equipment Information	Value or Feature Used in Modeling	Basis/Justification
1	HP combustor technology available	Not applicable	Long term CES development
1	HP steam/CO ₂ turbine technology available	Not applicable	Long term SPG development
1	IP steam/CO ₂ turbine inlet conditions	1760°C and 42.7 bar	Long term SPG development
1	IP steam/CO ₂ turbine outlet pressure	0.15 bar	Long term SPG development
1	Gasifier type	Full Slurry Quench	Same as near term
1	O ₂ compressor efficiency	No change from near term cycle	Same as near term
1	Air Separation Unit (ASU) aux load	0.200 kWh/kg	Same as near term
2	Low cooling demand of the IP turbine components	Turbine cooling & leakage steam (TCLC) at 15% of inlet flow.	Long term advancements in steam cooling technologies
3	ITM technology for oxygen separation	ITM supplies O ₂ to gasifier	Long term development in air separation technology
4	Advanced CO ₂ compressor	Assumed efficiency increase from the current 80% to 85% with DOE funded contracts.	Long term development in compressor technology (Reference 5 but no specific claims made about efficiency). Will require liquid phase compression instead of gaseous phase for reduction in compression load and, a refrigeration system with additional aux power requirement not otherwise required.

Discussion

Table 3 (below) lists the coal-to-grid HHV efficiencies for the four long-term cases identified above.

Case	Features	Coal-to-grid HHV efficiency
1	Same assumptions as near-term case for the auxiliaries; higher temperatures and pressures for the IP and HP turbines	35.6%
2	IPT steam cooling flow equal to 15% of inlet flow	37.6%
3	ITM supplies oxygen to gasifier, cryogenic ASU still needed for the combustor oxygen	38.8%
4	Advanced CO ₂ compressor with reduced auxiliary load	39.0% (tentative)

Table 3 shows that the expected coal-to-grid HHV efficiencies range between 35.6% and 39.0%, depending on the availability of supporting technologies by 2015.

A comparison between **Case 1** and **Case 2** shows that the effect of reducing the IPT cooling requirements from 25% to 15% of the IPT inlet flow is to increase the net cycle efficiency by 2 percentage points. This highlights the important benefits that may be derived from advancements in turbine cooling technologies.

In **Case 3**, an ITM system is integrated into the cycle to provide oxygen to the gasifier. In this configuration, the compressed air that comprises the ITM feed is directly heated by combustion with syngas to the temperature required by the membrane, i.e. ~875°C. The O₂ depleted air (non-permeate) stream is expanded through a turbo-expander to generate power, and heat is recovered from the expander exhaust by preheating feedwater and raising IP steam. This is shown in **Figure 3**.

1.1.1.1.1.1.1.1.1 Due to the large quantities of energy required to heat the compressed air, as well as integration issues with the power block, CES and SPG concluded that it was not feasible to use an ITM to supply all the oxygen requirements of the cycle. Hence, an ITM was only used to supply the gasifier, with cryogenic ASU's supplying the combustors. As is shown in Table 3, this leads to a 1.2% point increase in the cycle efficiency. However, direct syngas combustion in air produces CO₂ emissions that amount to approximately 8% of the CO₂ produced in the cycle, and is not captured.

In **Case 4**, the effect of potential advancements in CO₂ compression technology is considered. The work currently being done by Southwest Research Institute (SwRI) under DOE funding (Reference 5) is expected to lay the groundwork for development of compression technology and equipment that could further reduce the aux load of CO₂ compression. However, this technology will depend on compression of CO₂ in liquid phase instead of gaseous phase, requiring the incorporation of a refrigeration system which may add to the overall aux load. For the sake of modeling this novel approach, Case 4 assumes an increase in efficiency from the current 80% to 85%. A first approximation calculation indicates a small increase in the cycle

Since the long term (~ 2015) efficiency falls short of the DOE goal of 50% by almost 10 percentage points, SPG and CES are providing the following thoughts on how this gap might be closed notwithstanding the deadline of the year 2015.

- Gasifier efficiency
- Reduction in ASU aux load
- Further improvement in CO₂ compression efficiency
- Improvement in turbine efficiency and cooling flow management

In order to better understand the sensitivity of these factors to the overall plant efficiency, SPG has run some cases assuming modest improvements in each case. These cases are shown in **Table 4** along with the results.

Table 4: Effect on Plant Efficiency from Hypothetical Improvement in Plant Equipment

Plant Equipment	Assumed Improvement	Effect on Plant Efficiency (Not Cumulative, individual)
Gasifier	Increased cold gas efficiency from 80.32% to 85%	Approx. 1.75% points
Air Separation Unit (ASU)	25% reduction in the load for oxygen production - from 0.200 kWh/kg of oxygen to 0.150 kWh/kg of oxygen	Approx. 1.3% points
IP Gas Turbine	Cooling & leakage flow reduction from 15% to 10% of inlet flow	Approx. 1% point
CO ₂ compression equipment	Efficiency increase from 85% to 88%	Approx. 0.125% point
HP Steam Turbine	Isentropic efficiency increase from 88% to 90%	Not significant because the contribution to power from steam turbines is a small fraction of the total power

(Caution: These results must be considered as “first approximation” since simultaneous effects on other plant parameters are ignored. Collectively these improvements may increase the plant efficiency by approx. 4% points, but needs to be verified.)

The results show where future effort could be directed in order to improve the plant cycle efficiency and the preferred order to attain the largest ‘bang for the bucks’. (One other technology that has not been evaluated for lack of information is warm syngas cleanup. This technology has been mentioned as a way to reduce the aux load. However, it is not linked to the gasifier supplier and CES was unable to obtain sufficient information that could be used in modeling.)

Conclusions

CES and SPG have selected optimum oxy-syngas cycles for near-term (2010) and long-term (2015) scenarios. The near-term cycle utilizes a CES combustor to produce drive gas for a steam/CO₂ IPT with inlet conditions of 30 bar and 1450°C. The long-term cycle utilizes two CES combustors to drive a HP steam/CO₂ turbine with inlet conditions of 113 bar/760°C and a IP steam/CO₂ turbine with inlet conditions of 42.7 bar/1760°C.

Using reasonable assumptions (some still under verification) for near-term and long-term scenarios, CES and SPG conclude that the near-term (2010) oxy-syngas cycle can achieve a coal-to-grid HHV efficiency of 30.0%.

For long-term cases, the cycle efficiency ranges from 35.6 to 39% depending on the availability of supporting technologies that include advanced IPT cooling systems, ITM oxygen production, and advanced CO₂ compression technologies.

Additional improvements may be attained (beyond 2015) with further developments in gasifier cold gas efficiency, ASU aux loads, IPT cooling and CO₂ compression. With modest improvements in each of these, a collective impact of approx. 4% point improvement may be possible beyond the 39% stated above.

List of References

1. Email from Air Products (Vince White) to CES (Larry Trowsdale), dated January 9, 2006. The e-mail indicates an ASU auxiliary load of 0.200 kWh/kg O₂ for an ASU with 2 high pressure columns producing 95% pure O₂ at 1.6 bar (abs).
2. Data sheet from ConocoPhillips (David Breton) to CES (Scott MacAdam), sent 20 May, 2006 containing process information for the Full Slurry Quench (FSQ) and Entrained Slurry Transport Reactor (ESTR) gasification systems, using Illinois #6 coal.
3. Email from ConocoPhillips (David Breton) to CES (Scott MacAdam), dated 31 May, 2006, containing additional gasifier interface information. The e-mail indicates that the 'Hot BFW' interface stream is used as feedwater for the syngas cooler and to heat the syngas, with a small fraction used to supplement the syngas saturator. It also indicates that the import LP steam flow rate to the FSQ gasifier is 175.63 klb/hr (22.13 kg/s), or 0.2472 kg LP steam per kg dry syngas produced.
4. Email from ConocoPhillips (J.B. Thesee) to CES (Scott MacAdam), dated 1 June, 2006, containing additional gasifier interface information. The e-mail indicates that the FSQ Condensate Heater (E-163) is able to provide 145.8 MMBtu/hr in feedwater heating by cooling the syngas from 290°F (143.3°C) to 198°F (92.2°C). This corresponds to 0.4773 MW per kg dry syngas produced.
5. J. Jeffrey Moore, et al, 'Novel concepts for the compression of large volumes of CO₂': Quarterly progress report dated April 28, 2006 prepared by Southwest Research Institute, under DOE award DE-FC26-05NT-42650.

Appendix 1: Assumptions still to be verified with ConocoPhillips (COP)

No.	Parameter and Value Assumed	Reason for Assumption
1	Syngas temperature at the outlet of the gasification island is assumed to be 177 deg C as against the 271 deg C specified by COP	Per COP email, the wet syngas leaving the saturator is at the saturation temperature of 177 deg C at 20% (vol) moisture. It is then normally superheated to >260 deg C by the hot boiler feed water (HBFW). If the HBFW is not used for any other purpose, we can use the syngas at 177 deg C and reduce the HBFW input interface. Pending confirmation.
2	Assume only 5% of the total HBFW is going to the saturator and nothing is going to the super heater or other consumers. (Related to assumption 1 above)	Same as above plus need to verify if there are any other consumers such as syngas cooler, MP steam, moisturization etc. which may need additional extraction. Pending for details from COP on consumption and uses of HBFW.
3	LP steam consumption of 0.247 kg per kg/s is assumed instead of COP provided value 0.456 kg per kg/s of dry syngas.	There is a disconnect between the spreadsheet supplied by COP and information in COP email. Email indicates lower LP steam usage. It needs to be verified if there are other consumers of LP steam.
4	Gasifier aux load value is assumed to be 0.138 kWh/kg of dry syngas.	Based on COP spreadsheet and emails the value calculates to be 0.145 kWh/kg of syngas. (Needs to be verified).

Appendix 2: Assumptions still to be verified with compressor suppliers

No	Parameter and Value Assumed	Reason for Assumption
1	CO ₂ compressor efficiency is currently at 80%	Per discussions with Siemens PG-I, using a combination of internally gear and reciprocating compressors the efficiency is between 80-83%. Pending written confirmation.
2	O ₂ compressor efficiency is currently at 85%	Per discussions with Air Products, the oxygen compressor efficiency is between 83-87%. (Need independent verification from a compressor supplier.)

FINAL REPORT

ZEPP CYCLE PERFORMANCE ON NATURAL GAS AND IN COAL GASIFICATION (FULL AND PARTIAL QUENCH CASES)

Prepared By

Advanced Power and Energy Program

University of California, Irvine
August 2009

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Introduction

The systems analysis group at the Advanced Power and Energy Program (APEP) of the University of California, Irvine has been requested by Siemens to develop overall system simulations of two gas turbine based oxy-combustion cycles for Zero Emissions Power Plant (ZEPP) applications, one in natural gas application and the other in an integrated coal gasification plant application. The performance of the high pressure (HP) and the intermediate (IP) oxy-combustion turbines used in these cases are consistent with the natural gas fired "Gen 2 cycle" which originated with Clean Energy Systems (CES). Florida Turbine Technology (FTT), which is a Siemens gas turbine design arm, has worked with CES to identify design conditions for the SGT-900 IP turbine when operating on a steam/CO₂ mixture working fluid.

The performance for the warm gas cleanup process which was utilized in the coal case was provided by its developer, Research Triangle Institute (RTI).

Process Design Basis and Methodology

The following is the process design basis for the Coal Case.

Site Conditions

The plant is designed for the following mean ambient conditions (ISO conditions):

- Dry bulb temperature: 15°C
- Elevation: Mean Sea Level
- Relative Humidity: 60%

Mechanical draft cooling towers with 11°C temperature rise for the cooling water are used. The above ambient conditions correspond to a wet bulb temperature of 10.8°C. In the previous CES study, CES specified a cooling water supply temperature of 17.5°C which corresponds to a cooling water approach temperature of 6.7°C to the wet bulb temperature. However, it was agreed between APEP and Siemens that a cooling water supply temperature be specified as 15°C.

Natural Gas Feed

The characteristics of the natural gas feed are the same as that in the previous CES study and are shown in Table 2-1.

Table 2-1 Natural Gas Feed	
	vol%
Methane	94.24
Ethane	2.94
Propane	0.67
Butane	0.21
Carbon Dioxide	1.30
Nitrogen	0.64
Total	100.00
Temperature, °C	15
Pressure, bar(a)	20.68
Lower Heating Value, kJ/kg	47,607

Coal Feed

The characteristics of the coal feed are the same as that in the previous CES study and are shown in Table 2-2.

Table 2-2 Coal Feed (Illinois No. 6)		
Proximate Analysis, wt%		
	As Received	Dry
Moisture	7.97	0.00
Ash	14.25	15.48
Volatile Matter	36.86	40.05
Sulfur	4.45	4.83
Fixed Carbon (by difference)	36.47	39.64
Ultimate Analysis, wt%		
Moisture	7.97	0.00
Carbon	60.42	65.65
Hydrogen	3.89	4.23
Nitrogen	1.07	1.16
Chlorine	0.05	0.05
Sulfur	4.45	4.83
Ash	14.25	15.48
Oxygen (by difference)	7.90	8.60
Heating Values, kJ/kg / Btu/lb		
Higher Heating Value	25584 / 10999	27798 / 11951
Lower Heating Value		26864 / 11549

Gasifier and Warm Gas Cleanup Performances

Full Quench Gasifier

Siemens provided the performance of the gasifier while utilizing 99.6 mole % purity O₂ and N₂ for both lock hopper pressurization as well as for transporting the coal into the gasifier ("carrier gas"). From previous studies, it was determined that the CO₂ purity specification of 95% is not met when N₂ is used as the carrier gas. Thus the gasifier performance was adjusted by APEP using CO₂ as the carrier gas. Overall plant performances were developed for two cases, one utilizing a 99.6 mole % O₂ stream and the other with a lower purity of 96.5% O₂ stream. The higher purity O₂ stream which is consistent with that used by Siemens in developing the gasifier performance resulted in a CO₂ stream with a much higher purity with respect to its CO₂ content (> 95 mole % CO₂) than the required for enhanced oil recovery applications. The case with the

lower purity O₂ was then developed to reduce the parasitic power consumption of the air separation unit (ASU) since a potential exists to enhance the overall plant thermal efficiency while still meeting the > 95 mole % CO₂ specification. Furthermore, the capital cost of the ASU will be reduced when producing a lower purity O₂ stream.

The feed gas composition, temperature and pressure to the warm gas cleanup unit consisting of the syngas leaving the gasifier quench system for the 99.6 mole % purity O₂ case was provided to RTI. RTI developed the corresponding stream data and utility requirements for the warm gas cleanup and sulfuric acid production units. These data were then adjusted by APEP for the 96.5 mole % purity O₂ case.

Partial Quench Gasifier

The performance of the gasifier utilizing a 96.5% purity O₂ stream operating with a radiant syngas cooler followed by partial quenching of the raw syngas was estimated by APEP. The raw syngas was cooled in the radiant cooler to a temperature of 850°C (Siemens had stated that this temperature would typically be in the range of 800°C to 850°C). The syngas leaving the radiant cooler was next cooled to a temperature of 442°C by a water spray resulting in the "Partial Quench" design. This partially quenched syngas was then fed to the warm gas cleanup unit (RTI had stated that the desirable inlet temperature to their warm gas cleanup unit was in the range of 800°F to 850°F or 427°C to 454°C). APEP also estimated the performance of the warm gas cleanup unit as RTI was not able to provide its performance for this case.

Combustion and Gasification Oxygen

Natural Gas Case

The composition of the oxygen for oxy-combustion was provided in the CES study and is shown in Table 2-3. The temperature of the O₂ and utility requirements of the ASU for a required supply pressure correspond to a liquid pumped O₂ system and were estimated from information provided by CES (Air Products report to CES dated 7/12/06).

Table 2-3	
Oxygen for Combustion – Natural Gas Case	
	vol%

Oxygen	98.0
Argon	2.0
Total	100.00

Coal Case

The composition of the O₂ stream for the 96.5% and the 99.6% purity cases is shown in Table 2-4. The temperature of the O₂ and utility requirements of the ASU for a required supply pressure correspond to a liquid pumped O₂ system and were estimated from information provided by CES (Air Products report to CES dated 7/12/06).

Table 2-4		
Oxygen for Gasification and Combustion – Coal Case		
		vol%
Oxygen	96.5	99.6
Argon	2.5	0.4
Nitrogen	1.0	
Total	100.00	100.00

Carbon Dioxide Product Specification

The specifications of the CO₂ product were provided in the previous CES study (based on Kinder-Morgan specifications) and are shown in Table 2-5.

Table 2-5		
Carbon Dioxide Product Specifications		
Carbon Dioxide	≥ 95 vol%	MMP for EOR
Water	≤ 508 kg/Million Nm ³ (30 lb/MMSCF)	Pipeline Corrosion
Nitrogen	≤ 4 vol%	MMP for EOR

Hydrocarbons	≤ 5 vol%	MMP for EOR
Oxygen	≤ 10 ppmw	Pipeline Corrosion
Temperature	$\leq 48.9^{\circ}\text{C}$ (120°F)	Pipeline Corrosion
Pressure	151.7 bar(a) (2200 psia)	

MMP = Minimum Miscibility Pressure
EOR = Enhanced Oil Recovery

Makeup Water

Makeup water is required by the cycle for the HP Combustor injection [Boiler Feedwater (BFW) and Steam injection], steam drum blowdown (BD), deaerator vent, cooling tower and plant utility water. The BFW and steam injected into the combustor can be recovered as condensate from the flue gas. This condensate (in addition to the water vapor condensed as the HP combustor syngas is cooled downstream of the warm gas cleanup system prior to compression in the case of coal), is treated and then used as makeup to the steam system and cooling tower. Fresh makeup water is also required to supplement makeup to the cooling towers and is assumed to be fresh water without any “unusual” treatment requirements.

Power Cycle Design Parameters

- Fuel gas (natural gas and syngas) pressure
 - 6.9 bar (100 psi) above HP combustor pressure
 - 5 bar (73 psi) above Reheater of IP combustor pressure
- Turbine efficiencies (HPT, SGT-900 and Organic Fluid Turbine):
 - HPT isentropic efficiency = 89%
 - SGT-900 effective isentropic efficiency = 85.1% (includes work produced by cooling stream)
 - Organic Rankine Cycle Turbine isentropic efficiency = 85%
- Combustor exit conditions:
 - **HP Combustor: 538°C (1000°F) and 82.8 bar(a) (1200 psia).** The combustor excess O_2 is set at 0.95% based on the previous CES work, which in turn sets the ratio of the O_2 flow rate to the natural gas flow rate. The required HPT inlet temperature of 538°C or 1000°F is achieved by varying HP BFW injection to the combustor while the steam injection flow is maximized.
 - **Reheater (IP Combustor): 1080°C (1976°F) and 15.6 bar(a) (227 psia).** The combustor excess O_2 is set at 1.93% again based on the previous CES

work. The IP turbine inlet temperature of 996°C or 1824°F (temperature after mixing with the blade cooling stream which consists of a mixture of primarily H₂O and CO₂) is achieved by adjusting the flow rate of natural gas to the IP combustor. The flow rate through the turbine is maintained to be within 1% of the target flow rate of 559,056 kg/hr (1,232,718 lb/hr) by scaling the flow rate of the streams entering both the HP combustor and the IP combustor/turbine to match the overall size of the plant.

- Heat losses:
 - Combustor and reheater heat losses = 0.2% of LHV of fuel entering each combustor
 - Heat Recovery Unit downstream of SGT-900 = 0.5% and 1°C temperature drop from turbine exhaust to inlet of heat recovery unit.

Property Packages

The performance of the plant was estimated using the Aspen Plus Simulator software, and the following property packages were used to model the cycle:

- PR-BM (Peng-Robinson equation of state with Boston-Mathias modifications) for fuel gas (natural gas and syngas), low pressure flue gas and oxygen
- SR –Polar (Schwartzentruber-Renon equation of state for highly non-ideal systems) for high purity, high pressure carbon dioxide
- STEAM-TA (ASME 1967 Steam Table Corrections) for the water and steam.

Units of Measurement

Performance calculations are performed using English units. The units presented in the report are modified SI as specified by Siemens. Both units of measurements are provided when appropriate.

Plant Description and Performance

Natural Gas Case

The following deliverables are included:

- Table 3-1 – Overall Plant Performance Summary
- Table 3-2 – Gas Turbine Losses
- Table 3-3 – Balance of Plant Power Consumption
- Process Description
- Drawing BFD-001 – Overall Block Flow Diagram
- Table 3-4 – Corresponding stream data for Overall Block Diagram (BFD-001)
- Drawing BFD-002 – Heat Recovery Steam Generator (HRSG) and Organic Fluid Cycle Block Flow Diagram
- Drawing BFD-003 – CO₂ Compression Block Flow Diagram
- Table 3-5 – Corresponding stream data for CO₂ Compression Block Diagram (BFD-003)

**Table 1
Siemens
Natural Gas Case
Overall Plant Performance Summary**

Natural Gas Fuel Rate, kg/hr	34,911
GJ/hr (HHV)	1,840
GJ/hr (LHV)	1,662
Power Generation, kWe	
Gas Turbine	192,452
Organic Fluid Turbine	28,324
Gross Power Generation	220,776
Auxiliary Power Consumption, kWe	
Natural Gas Booster Compressor	1,457
Balance of Plant	62,852
Net Plant Output, kWe	156,466
Generation Efficiency (HHV)	
Net Heat Rate, kJ/kWh	11,757
% Fuel to Power	30.6
Generation Efficiency (LHV)	
Net Heat Rate, kJ/kWh	10,622
% Fuel to Power	33.9

**Table 3-2
Natural Gas Fired ZEPP Cycle
Gas Turbine Losses**

Turbine	Net Output, kWe	Mech & Gen Losses, kWe
High Pressure	51,252	1,046
SGT-900	141,200	2,882
Total Gas Turbine	192,452	3,928

**Table 3-3
Natural Gas Fired ZEPP Cycle
Balance of Plant Power Consumption**

	kWe
Air Separation Unit	42,486
CO ₂ Compressor	12,738
Boiler Feedwater Pumps	2,472
Cooling Tower and Pumps	4,074
Gas Turbine Auxiliaries	313
Organic Fluid Turbine Auxiliaries	42
General Makeup and Demineralized Water	91
Miscellaneous Balance-of-Plant and Lighting	158
Transformer Losses	478
Total Auxiliary Power Consumption	62,852

Process Description

The natural gas fired plant consists of the following process units:

- Air Separation Unit (ASU)
- Natural Gas Compression
- Gas Turbine
 - HP Combustor
 - HP Turbine
 - IP Combustor
 - IP Turbine
- Heat Recovery Unit
- Organic Rankine Cycle (ORC)
- Flue Gas Condenser
- CO₂ Compression System including Dehydration and Catalytic Combustion (to reduce its O₂ content)

The plant also has the necessary utilities (e.g. cooling water supply, make-up water treatment, plant and instrument air).

The configuration of the plant is shown in the Overall Block Flow Diagram, BFD-001 while the corresponding stream data are presented in Table 3-4. Natural gas required by the HP

combustor is compressed while that required by the IP combustor is fed directly without the need for compression as the supply pressure of natural gas suffices. Oxygen required for the combustion is provided by an on-site air separation unit (ASU). The HP combustor is cooled by HP steam and boiler feed water (BFW). The HP combustor exhaust is routed directly to the HP turbine. Majority of the exhaust from the HP turbine is supplied to the IP combustor while the remainder enters the IP turbine for blade cooling.

The resulting exhaust gas from the IP Turbine, consisting mostly of water and carbon dioxide, is routed to the heat recovery unit. This unit includes the HRSG to provide heat for superheating and producing steam and preheating BFW, and coils for the bottoming ORC to recover a significant fraction of the low temperature heat of condensation as the flue gas is cooled below its dew point. The working fluid used in the ORC consists of normal pentane based on information received from Ormat. This entire heat recovery system is depicted in Drawing BFD-002.

The flue gas leaving the heat recovery unit is then routed to a condenser where the heat of condensation is rejected to cooling water. The condensate thus produced after degassing and polishing is used for make-up to the steam system. The remaining (vapor) stream from the condenser is a relatively pure carbon dioxide stream (> 95 vol% CO_2). As depicted in Drawing BFD-003, this stream is compressed, preheated in a feed/effluent heat exchanger and then fed into a catalytic combustion unit where additional natural gas is supplied to reduce the O_2 content to meet the specifications of the product CO_2 . Heat recovery downstream of the catalytic combustion unit is accomplished by preheating BFW as well as the oxygen streams. Next, the stream is cooled in a trim cooler, dehydrated and compressed in an intercooled compressor to the final pressure as specified in the design basis. Stream data for this subsystem are presented Table 3-5.

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Table3- 4 Siemens Natural Gas Fired ZEPP Cycle Overall Block Diagram (BFD-001) Heat and Material Balances Process Streams																
BFD Stream number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Stream Name	Total Natural Gas Feed	Natural Gas to Compressor	Natural Gas to Reheater	Natural Gas to Catalytic Combustor	HP Oxygen to Preheater	HP Combustor Exhaust	HP Turbine Exhaust to Reheater	IP Oxygen to Preheater	Reheater Exhaust	IP Turbine Inlet (SGT 900)	Flue Gas from HRSG	Flue Gas Condensate from HRSG	Flue Gas from Condenser	Flue Gas Condensate from Condenser	Compressed CO ₂ Product	Condensate from CO ₂ Compression
	VAPOR	VAPOR	VAPOR	VAPOR	VAPOR	VAPOR	VAPOR	VAPOR	VAPOR	VAPOR	VAPOR	LIQUID	VAPOR	LIQUID	VAPOR	LIQUID
Mole Flow kmol/hr																
O ₂	0.0	0.0	0.0	0.0	2,018.6	32.7	28.3	2,118.3	61.8	66.2	66.2	0.0	66.2	0.0	0.0	0.0
CH ₄	1,915.9	919.7	965.5	30.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
H ₂ O	0.0	0.0	0.0	0.0	0.0	23,560.9	20,380.2	0.0	22,439.8	25,620.6	3,232.2	22,388.4	66.0	3,166.2	0.0	121.5
CO ₂	26.4	12.7	13.3	0.4	0.0	1,017.6	880.2	0.0	1,948.5	2,085.9	2,085.6	0.3	2,085.6	0.0	2,119.5	0.0
C ₂ H ₆	59.8	28.7	30.1	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C ₃ H ₈	13.6	6.5	6.9	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C ₄ H ₁₀	4.3	2.0	2.2	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C ₅ H ₁₂	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
N ₂	13.0	6.2	6.6	0.2	0.0	6.2	5.4	0.0	12.0	12.8	12.8	0.0	12.8	0.0	13.0	0.0
AR	0.0	0.0	0.0	0.0	41.2	41.2	35.6	43.2	78.9	84.4	84.4	0.0	84.4	0.0	84.4	0.0
Mole Frac																
O ₂	0.00	0.00	0.00	0.00	0.98	0.00	0.00	0.98	0.00	0.00	0.01	0.00	0.03	0.00	0.00	0.00
CH ₄	0.94	0.94	0.94	0.94	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
H ₂ O	0.00	0.00	0.00	0.00	0.00	0.96	0.96	0.00	0.91	0.92	0.59	1.00	0.03	1.00	0.00	1.00
CO ₂	0.01	0.01	0.01	0.01	0.00	0.04	0.04	0.00	0.08	0.07	0.38	0.00	0.90	0.00	0.96	0.00
C ₂ H ₆	0.03	0.03	0.03	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C ₃ H ₈	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C ₄ H ₁₀	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C ₅ H ₁₂	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
N ₂	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.01	0.00
AR	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.02	0.00	0.00	0.02	0.00	0.04	0.00	0.04	0.00
Total Flow kmol/hr	2,033.0	975.9	1,024.5	32.5	2,059.8	24,658.7	21,329.8	2,161.5	24,541.0	27,869.9	5,481.2	22,388.7	2,315.0	3,166.2	2,217.0	121.5
Total Flow kg/hr	34,910	16,758	17,593	559	66,239	472,109	408,375	69,510	495,478	559,212	155,866	403,346	98,825	57,042	97,016	2,189
Total Flow cum/sec	0.619	0.297	0.312	0.010	0.140	5.265	16.639	0.803	49.056	52.231	42.102	0.139	15.705	0.019	0.036	0.001
Temperature C	15.0	15.0	15.0	15.0	11.1	537.8	308.2	11.1	1079.3	995.6	89.1	89.1	26.1	26.1	26.1	26.1
Pressure bar	20.68	20.68	20.68	20.68	89.98	82.74	16.55	17.37	15.64	15.64	1.08	1.08	1.01	1.01	151.72	6.97
Vapor Frac	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	1.00	0.00	1.00	0.00
Liquid Frac	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	1.00	0.00	1.00

Table 3-4 (cont'd) Siemens Natural Gas Fired ZEPP Cycle Overall Block Diagram (BFD-001) Heat and Material Balances Steam/Water Streams															
BFD Stream number	100	101													
Stream Name	HP BFW to HP Combustor	HP Steam to HP Combustor													
	LIQUID	VAPOR													
Mole Flow kmol/hr															
H2O	19,729.2	1,869.5													
Mole Frac															
H2O	1.00	1.00													
Total Flow kmol/hr	19,729.2	1,869.5													
Total Flow kg/hr	355,428	33,679													
Total Flow cum/sec	0.138	0.226													
Temperature C	299.1	336.4													
Pressure bar	96.53	90.99													
Vapor Frac	0.00	1.00													
Liquid Frac	1.00	0.00

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Table 3-5 Siemens Natural Gas Fired ZEPP Cycle CO ₂ Compression Block Diagram (BFD-003) Heat and Material Balances															
BFD Stream number	17	13	14	4	18	19	16	20	21	15					
Stream Name	Flue Gas from Condenser	CO ₂ to 1st Stage of Compression	Flue Gas Condensate	Natural Gas to Catalytic Combustor	CO ₂ from Catalytic Combustor	CO ₂ from Separator	Condensate from Separator	Dry CO ₂	Condensate for Recycle	CO ₂ Product					
	MIXED	VAPOR	LIQUID	VAPOR	VAPOR	VAPOR	LIQUID	VAPOR	LIQUID	VAPOR					
Mole Flow kmol/hr															
O ₂	66.2	66.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0					
CH ₄	0.0	0.0	0.0	30.7	0.0	0.0	0.0	0.0	0.0	0.0					
H ₂ O	3,232.2	66.0	3,166.2	0.0	131.4	9.9	121.5	0.0	3,287.7	0.0					
CO ₂	2,085.6	2,085.6	0.0	0.4	2,119.5	2,119.5	0.0	2,119.5	0.0	2,119.5					
C ₂ H ₆	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0					
C ₃ H ₈	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0					
C ₄ H ₁₀	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0					
C ₅ H ₁₂	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0					
N ₂	12.8	12.8	0.0	0.2	13.0	13.0	0.0	13.0	0.0	13.0					
AR	84.4	84.4	0.0	0.0	84.4	84.4	0.0	84.4	0.0	84.4					
Mole Frac															
O ₂	0.01	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00					
CH ₄	0.00	0.00	0.00	0.94	0.00	0.00	0.00	0.00	0.00	0.00					
H ₂ O	0.59	0.03	1.00	0.00	0.06	0.00	1.00	0.00	1.00	0.00					
CO ₂	0.38	0.90	0.00	0.01	0.90	0.95	0.00	0.96	0.00	0.96					
C ₂ H ₆	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.00					
C ₃ H ₈	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00					
C ₄ H ₁₀	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00					
C ₅ H ₁₂	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00					
N ₂	0.00	0.01	0.00	0.01	0.01	0.01	0.00	0.01	0.00	0.01					
AR	0.02	0.04	0.00	0.00	0.04	0.04	0.00	0.04	0.00	0.04					
Total Flow kmol/hr	5,481.2	2,315.0	3,166.2	32.5	2,348.3	2,226.8	121.5	2,217.0	3,287.7	2,217.0					
Total Flow kg/hr	155,866	98,825	57,042	559	99,383	97,194	2,189	97,016	59,231	97,016					
Total Flow cum/sec	15.723	15.705	0.019	0.010	5.849	2.127	0.001	2.359	0.019	0.036					
Temperature C	26.1	26.1	26.1	15.0	699.9	26.1	26.1	26.1	26.1	26.1					
Pressure bar	1.01	1.01	1.01	20.68	9.04	6.97	6.97	6.28	1.38	151.72					
Vapor Frac	0.42	1.00	0.00	1.00	1.00	1.00	0.00	1.00	0.00	1.00					
Liquid Frac	0.58	0.00	1.00	0.00	0.00	0.00	1.00	0.00	1.00	0.00					

Coal Case – Full Quench Gasifier

The following deliverables are provided:

- Table 3-6 – Overall Plant Performance Summary for the 96.5% and the 99.6% O₂ purity cases
- Table 3-7 – Gas Turbine Losses for the 96.5% and the 99.6% O₂ purity cases
- Table 3-8 – Balance of Plant Power Consumption for the 96.5% and the 99.6% O₂ purity cases
- Process Description
- Drawing BFD-004 – Overall Block Flow Diagram
- Drawing BFD-005 – Steam System Block Flow Diagram showing the plant heat integration layout
- Drawing BFD-006 – CO₂ Compression Block Flow Diagram
- Table 3-9 – Major stream data for above three Block Flow Diagram for the 96.5% O₂ purity case.

Process Description

The coal based plant employing the full quench gasifier consists of the following process units:

- ASU
- Coal Feed Preparation
- Gasification [based on SIEMENS Fuel Gasifier (SFG) technology]
- High Temperature Quench Syngas Cooling and Scrubbing
- RTI's Warm Gas Cleanup including Acid (H₂SO₄) Unit
- Low Temperature Syngas Cooling and Compression of HP Turbine Fuel
- Syngas Expansion in a Turbo-expander for Energy Recovery from IP Turbine Fuel
- Gas Turbine (based on proposed SIEMENS technology)
 - HP Combustor
 - HP Turbine
 - IP Combustor
 - IP Turbine
- Heat Recovery Unit
- ORC
- Flue Gas Condenser
- CO₂ Compression System including Dehydration and Catalytic Combustion (to reduce its O₂ content)

The plant also has the necessary utilities (e.g. cooling water supply, make-up water treatment, plant and instrument air) to support the process units.

The configuration of the plant is shown in the Overall Block Flow Diagram, BFD-004 while the corresponding stream data are presented in Table 3-9. O₂ for gasification, combustion as well as that required in the acid plant are provided by an on-site ASU. O₂ is preheated first against steam before it is injected into the gasifier or the two combustors. In order to minimize the amount of CO₂ vented to the atmosphere, N₂ is used to pressurize the lock hoppers in the gasification unit while CO₂ is used for transporting the coal into the gasifier in order to minimize the N₂ content of the captured CO₂ such that the required purity specification of > 95% CO₂ is met. Natural gas is also provided to the gasifier to maintain a pilot flame. SIEMENS specifically uses natural gas instead of syngas for this purpose (possibly due to safety considerations since availability of syngas cannot be guaranteed at all times).

The “as received” coal, with a moisture content of 7.97 wt%, is dried to a moisture content of 1.5 wt% and then fed to the gasifier. The energy for drying the coal is supplied by steam. The gasifier operates at a temperature and pressure of 1450°C and 42 bar(a). The syngas, at 1450°C, is cooled by direct contact with water in a quench system. The quench water is primarily recycle water. A portion of the quench water is blown down from the plant in order to limit the chloride buildup. This waste water after primary treatment is disposed off in Class 1 deep injection well.

The syngas is supplied to RTI’s warm gas cleanup unit for removal of sulfur compounds as well as trace contaminants. The performance of this unit which includes production of H₂SO₄ was provided by RTI. A small fraction of the clean syngas required by the RTI unit is removed and then approximately 42% of the remaining clean syngas which is required by the HP combustor is cooled in a series of heat exchangers:

1. HP syngas preheater
2. Medium pressure (MP) steam generator
3. Low pressure (LP) steam generator
4. Vacuum condensate and makeup BFW preheater
5. Trim cooler where heat is rejected to cooling water.

The cooled syngas is then compressed, preheated in the HP syngas preheater, and then supplied to the HP combustor. Remainder of the clean syngas is expanded in a turbo-generator, preheated and then provided to the IP combustor.

The HP combustor is cooled by HP steam and boiler feed water (BFW). The HP combustor exhaust is routed directly to the HP turbine. Majority of the exhaust from the HP turbine is supplied to the IP combustor while the remainder enters the IP turbine for blade cooling.

The resulting flue gas from the IP Turbine, consisting mostly of water and carbon dioxide, is routed to the heat recovery unit. This unit includes the HRSG to provide heat for superheating and producing steam and preheating BFW, and coils for the bottoming ORC to recover a significant fraction of the low temperature heat of condensation as the flue gas is cooled below its dew point. The working fluid used in the ORC consists of normal pentane based on

information received from Omat. The steam, BFW and condensate system is depicted in Drawing BFD-005.

The flue gas leaving the heat recovery unit is then routed to a condenser where the heat of condensation is rejected to cooling water. The condensate thus produced after degassing and polishing is used for make-up to the steam system. The remaining (vapor) stream from the condenser is a relatively pure carbon dioxide stream ($> 95 \text{ vol\% CO}_2$). As depicted in Drawing BFD-006, this stream is compressed, preheated in a feed/effluent heat exchanger and then fed into a catalytic combustion unit where additional natural gas is supplied to reduce the O_2 content to meet the specifications of the product CO_2 . Heat recovery downstream of the catalytic combustion unit is accomplished by preheating BFW as well as the oxygen streams. Next, the stream is cooled in a trim cooler, dehydrated and compressed in an intercooled compressor to the final pressure as specified in the design basis. Stream data for this subsystem are presented Table 3-10.

Table 3-6
Coal Gasification based ZEPP Cycle
Overall Plant Performance Summary
Full Quench Gasifier Cases

Oxygen Purity, %	96.50	99.60
Coal Feed Rate, ST/D (MF)	1,679	1,688
MMBtu/hr (HHV)	1,672	1,682
MMBtu/hr (LHV)	1,616	1,625
Coal Feed Rate, MT/D (MF)	1,523	1,532
GJ/hr (HHV)	1,764	1,774
GJ/hr (LHV)	1,705	1,714
Natural Gas		

MMBtu/hr (HHV)	18	18
MMBtu/hr (LHV)	16	16
GJ/hr (HHV)	19	19
GJ/hr (LHV)	17	17
Power Generation, kWe		
Gas Turbine	168,855	169,652
Steam Turbine	4,464	4,514
ORC Turbine	18,890	19,890
Syngas Expander	2,961	2,957
Total Power Generated	195,170	197,013
Auxiliary Power Consumption, kWe	73,965	75,327
Net Plant Output, kWe	121,204	121,686
Generation Efficiency (HHV)		
Net Heat Rate, Btu/kWh	13,943	13,967
Net Heat Rate, kJ/kWh	14,707	14,710
% Fuel to Power	24.48	24.44
Generation Efficiency (LHV)		
Net Heat Rate, Btu/kWh	13,465	13,489
Net Heat Rate, kJ/kWh	14,203	14,228
% Fuel to Power	25.35	25.30

Table 3-7
Coal Gasification based ZEPP Cycle
Gas Turbine Losses
Full Quench Gasifier Cases

Oxygen Purity, %	96.50		99.60	
Turbine	Net Output, kWe	Mech & Gen Losses, kWe	Net Output, kWe	Mech & Gen Losses, kWe
High Pressure	39,598	808	39,888	814
SGT-900	129,257	2638	129,764	2648
Total Gas Turbine	168,855	3446	169,652	3462

**Table 3-8
Coal Gasification based ZEPP Cycle
Balance of Plant Power Consumption
Full Quench Gasifier Cases**

Oxygen Purity, %	96.50	99.60
	kWe	kWe
Coal Handling, Milling and Drying	2,214	2,227
Gasifier System	1,576	1,584
Air Separation Unit	40,032	41,977
Syngas Compressor	2,288	2,283
CO2 Compressor	18,681	18,004
Warm Gas Cleanup & H2SO4 Unit	2,551	2,566
BFW and Steam Condensate Pumps	1,655	1,671
Cooling Tower Fans and Pumps	4,227	4,266
Gas Turbine Auxiliaries	275	276
Steam Turbine Auxiliaries	15	15
ORC Turbine Auxiliaries	28	29
General Makeup and Demineralized Water	2	2
Transformer Losses	423	427
Total Auxiliary Power Consumption	73,965	75,327

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Table 3-9 Coal Gasification based ZEPP Cycle Stream Data Full Quench Gasifier Overall Block Diagrams (BFD-004, 005 & 006) - 96.5% O ₂ Purity Case															
BFD Stream No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Temperature C	15	26.7		11.1	27	350	40	60	60	208.5	27	15	243.4	143.9	11.1
Pressure bar	1.014	60.66	1.014	48.346	61.655	48	49	36.376	1.014	38.1	61.655	1.014	35.487	42.413	1.393
Vapor Frac	Solid (As Received)	1	Solid	1	1	1	1	0	Solid (Dry Basis)	1	1	1	1	1	1
Mole Flow kmol/hr		282.4326		1438.785	254.0516	583.9648	19.35852	1006.426		11323.37	116.5293	689.2056	11433.28	8.595901	56.6915
Mass Flow kg/hr	68,938	7911.922	64,421	46267.97	11080.06	10520.29	332.4181	18135.66	10,656.79	222385	5082.25	19886.5	225823.4	240.7965	1823.069
Component Mole Flow kmol/hr															
O2		0		1388.43	0.001784	0	0	0		0	0.000713	143.1481	0.000713	0	54.70742
N2		282.4326		14.38762	4.483624	0	0.123782	0.001427		41.87296	2.056495	532.2046	43.92945	8.595901	0.566829
AR		0		35.9678	7.127638	0	0	0.006421		43.08902	3.269346	6.478407	46.35837	0	1.417252
H2		0		0	0	0	0	0.148753		1560.187	0	0	1560.187	0	0
CO		0		0	0	0	0	0.124139		3413.677	0	0	3413.677	0	0
CO2		0		0	242.4382	0	0.251488	0.081689		238.7422	111.2027	0.206898	355.3064	0	0
H2O		0		0	0	583.9648	0	1005.632		5922.681	0	7.167591	6012.942	0	0
CH4		0		0	0	0	18.24342	0		0.822241	0	0	0.822241	0	0
H2S		0		0	0	0	0	0.210109		90.30744	0	0	0.04673	0	0
NH3		0		0	0	0	0	0.212962		6.563663	0	0	0	0	0
COS		0		0	0	0	0	0.006778		5.165317	0	0	0.010345	0	0
HCl		0		0	0	0	0	0.001427		0.125922	0	0	0	0	0
HCN		0		0	0	0	0	0		0.133057	0	0	0	0	0
SO2		0		0	0	0	0	0		0	0	0	0	0	0
C2H6		0		0	0	0	0.56897	0		0	0	0	0	0	0
C3H8		0		0	0	0	0.129846	0		0	0	0	0	0	0
C4H10-01		0		0	0	0	0.040666	0		0	0	0	0	0	0
C5H12-01		0		0	0	0	0	0		0	0	0	0	0	0
H2SO4				0	0	0	0	0		0	0	0	0	0	0

Table 3-9 (Cont'd.) Coal Gasification based ZEPP Cycle Stream Data Full Quench Gasifier Overall Block Diagrams (BFD-004, 005 & 006) - 96.5% O ₂ Purity Case															
BFD Stream No.	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Temperature C	15	20	43.3	243.4	235	243.4	221.4	148.9	305.1	141	538	309.6	148.9	996	565.5
Pressure bar	1.014	1.014	1.014	35.487	20.684	35.487	89.287	89.632	92.25	104.63	82.737	16.547	17.002	15.637	1.103
Vapor Frac	1	0	1	1	1	1	1	1	1	0	1	1	1	1	1
Mole Flow kmol/hr	291.3028	97.32521	849.0005	61.83077	6521.526	4849.923	2301.685	1104.348	8279.581	8230.291	18860.96	18860.96	1474.594	25438.52	25438.52
Mass Flow kg/hr	8405.321	9375.34	24148.02	1221.247	128809.3	95792.81	49883.94	35513.25	149159	148271	382825.6	382825.6	47419.51	559056.4	559056.4
Component Mole Flow kmol/hr															
O2	60.50377	0	67.63605	0	0.000357	0.000357	0.000357	1065.697	0	0	10.02885	10.02885	1422.985	13.48547	13.48547
N2	224.9442	0	766.3112	0.237576	25.0575	18.63474	18.63474	11.04336	0	0	29.67774	29.67774	14.74577	69.48065	69.48065
AR	2.738189	0	10.63385	0.250775	26.44264	19.66495	19.66352	27.60734	0	0	47.27086	47.27086	36.86317	110.5767	110.5767
H2	0	0	0	8.437517	889.9285	661.8213	661.8148	0	0	0	0	0	0	0	0
CO	0	0	0	18.46102	1947.156	1448.06	1448.056	0	0	0	0	0	0	0	0
CO2	0.087397	0	0.087397	1.921655	202.6663	150.7188	150.6543	0	0	0	1599.063	1599.063	0	3749.361	3749.361
H2O	3.02963	2.126413	4.114775	32.51796	3429.773	2550.651	2.488841	0	8279.581	8230.291	17174.89	17174.89	0	21495.56	21495.56
CH4	0	0	0	0.004281	0.469088	0.348873	0.348873	0	0	0	0	0	0	0	0
H2S	0	0	0	0.000357	0.026754	0.01962	0.01962	0	0	0	0	0	0	0	0
NH3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
COS	0	0	0	0	0.006064	0.004637	0.004281	0	0	0	0	0	0	0	0
HCl	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
HCN	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SO2	0	0	0.217243	0	0	0	0	0	0	0	0.0239	0.0239	0	0.056362	0.056362
C2H6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C3H8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C4H10-01	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C5H12-01	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
H2SO4	0	95.19844	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 3-9 (Cont'd.) Coal Gasification based ZEPP Cycle Stream Data Full Quench Gasifier Overall Block Diagrams (BFD-004, 005 & 006) - 96.5% O ₂ Purity Case															
BFD Stream No.	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45
Temperature C	94.8	60	26.8	90.3	26.1	47.5	26.1	185.5	158.8	32.2	47	141	482.2	516.2	26.1
Pressure bar	4.137	0.724	5.171	1.032	0.963	4.482	151.685	11.36	6	0.048	1.014	4.46	28.04	27.35	26.661
Vapor Frac	1	1	0	0.439	1	0	1	1	0.995	0.833	0	0	1	1	1
Mole Flow kmol/hr	17192.91	17192.91	17192.91	25438.52	3944.605	21529.18	3579.676	446.9198	1478.278	1478.278	18225.13	24291.19	3944.605	3992.987	3957.717
Mass Flow kg/hr	1240475	1240475	1240475	559056.4	171837.1	387855.4	156122	8051.385	26631.6	26631.6	328330.8	437614.4	171837.1	173058.4	172421.3
Component Mole Flow kmol/hr															
O2	0	0	0	13.48547	13.48547	0	0.024392	0	0	0	0	0	13.48547	0.026754	0.026754
N2	0	0	0	69.48065	69.48065	0	63.17794	0	0	0	0	0	69.48065	69.71823	69.71823
AR	0	0	0	110.5767	110.5767	0	100.4305	0	0	0	0	0	110.5767	110.8274	110.8274
H2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CO	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CO2	0	0	0	3749.361	3749.361	0.06421	3416.043	0	0	0	0	0	3749.361	3769.748	3769.684
H2O	0	0	0	21495.56	1.64484	21529.12	0	446.9198	1478.278	1478.278	18225.13	24291.19	1.64484	42.60923	7.404097
CH4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
H2S	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
NH3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
COS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
HCl	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
HCN	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SO2	0	0	0	0.056362	0.056362	0.000357	0	0	0	0	0	0	0.056362	0.056719	0.056719
C2H6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C3H8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C4H10-01	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C5H12-01	17192.91	17192.91	17192.91	0	0	0	0	0	0	0	0	0	0	0	0
H2SO4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

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Coal Case – Partial Quench Gasifier

The following deliverables are provided:

- Table 3-10 – Overall Plant Performance Summary comparing the Partial Quench Case with the previous Full Quench Case, both with the 96.5% O₂ purity
- Table 3-11 – Gas Turbine Losses comparing the Partial Quench Case with the previous Full Quench Case, both with the 96.5% O₂ purity
- Table 3-12 – Balance of Plant Power Consumption comparing the Partial Quench Case with the previous Full Quench Case, both with the 96.5% O₂ purity
- Process Description
- Drawing BFD-007 – Overall Block Flow Diagram for the Partial Quench Case
- Drawing BFD-008 – Steam System Block Flow Diagram showing the plant heat integration layout for the Partial Quench Case
- Drawing BFD-009 – CO₂ Compression Block Flow Diagram for the Partial Quench Case
- Table 3-13 – Major stream data for above three Block Flow Diagram for the Partial Quench Case.

Process Description

The coal based plant employing the partial quench gasifier consists of the following process units:

- ASU
- Coal Feed Preparation
- Gasification [based on SIEMENS Fuel Gasifier (SFG) technology]
- High Temperature Radiant Syngas Cooling and Partial Quenching
- RTI's Warm Gas Cleanup including Acid (H₂SO₄) Unit
- Low Temperature Syngas Cooling and Compression of HP Turbine Fuel
- Syngas Expansion in a Turbo-expander for Energy Recovery from IP Turbine Fuel
- Gas Turbine (based on proposed SIEMENS technology)
 - HP Combustor
 - HP Turbine
 - IP Combustor
 - IP Turbine
- Heat Recovery Unit
- ORC
- Flue Gas Condenser
- CO₂ Compression System including Dehydration and Catalytic Combustion (to reduce its O₂ content)

The plant also has the necessary utilities (e.g. cooling water supply, make-up water treatment, plant and instrument air) to support the process units.

The configuration of the plant is shown in the Overall Block Flow Diagram, BFD-007 while the corresponding stream data are presented in Table 3-13. O_2 for gasification, combustion as well as that required in the acid plant are provided by an on-site ASU. O_2 is preheated first against steam before it is injected into the gasifier or the two combustors. In order to minimize the amount of CO_2 vented to the atmosphere, N_2 is used to pressurize the lock hoppers in the gasification unit while CO_2 is used for transporting the coal into the gasifier in order to minimize the N_2 content of the captured CO_2 such that the required purity specification of $> 95\%$ CO_2 is met. Natural gas is also provided to the gasifier to maintain a pilot flame. SIEMENS specifically uses natural gas instead of syngas for this purpose (possibly due to safety considerations since availability of syngas cannot be guaranteed at all times).

The “as received” coal, with a moisture content of 7.97 wt%, is dried to a moisture content of 1.5 wt% and then fed to the gasifier. The energy for drying the coal is supplied by steam. The gasifier operates at a temperature and pressure of 1450°C and 42 bar(a). The syngas, at 1450°C, is cooled in a radiant syngas cooler to a temperature of 850°C. The syngas leaving the radiant cooler is next cooled to a temperature of 442°C by a water spray and then fed to the warm gas cleanup unit. The quench water is primarily recycle water.

The syngas is supplied to RTI’s warm gas cleanup unit for removal of sulfur compounds as well as trace contaminants. The performance of this unit which includes production of H_2SO_4 was estimated by APEP. A small fraction of the clean syngas required by the RTI unit is removed and then approximately 42% of the remaining clean syngas which is required by the HP combustor is cooled in a series of heat exchangers:

1. HP syngas preheater
2. Medium pressure (MP) steam generator
3. Low pressure (LP) steam generator
4. Vacuum condensate and makeup BFW preheater
5. Trim cooler where heat is rejected to cooling water.

The cooled syngas is then compressed, preheated in the HP syngas preheater, and then supplied to the HP combustor. Remainder of the clean syngas is expanded in a turbo-generator, preheated and then provided to the IP combustor.

The HP combustor is cooled by HP steam and boiler feed water (BFW). The HP combustor exhaust is routed directly to the HP turbine. Majority of the exhaust from the HP turbine is supplied to the IP combustor while the remainder enters the IP turbine for blade cooling.

The resulting flue gas from the IP Turbine, consisting mostly of water and carbon dioxide, is routed to the heat recovery unit. This unit includes the HRSG to provide heat for superheating and producing steam and preheating BFW, and coils for the bottoming ORC to recover a significant fraction of the low temperature heat of condensation as the flue gas is cooled below its dew point. The working fluid used in the ORC consists of normal pentane based on information received from Ormat. The steam, BFW and condensate system is depicted in Drawing BFD-008.

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The flue gas leaving the heat recovery unit is then routed to a condenser where the heat of condensation is rejected to cooling water. The condensate thus produced after degassing and polishing is used for make-up to the steam system. The remaining (vapor) stream from the condenser is a relatively pure carbon dioxide stream (> 95 vol% CO_2). As depicted in Drawing BFD-009, this stream is compressed, preheated in a feed/effluent heat exchanger and then fed into a catalytic combustion unit where additional natural gas is supplied to reduce the O_2 content to meet the specifications of the product CO_2 . Heat recovery downstream of the catalytic combustion unit is accomplished by preheating BFW as well as the oxygen streams. Next, the stream is cooled in a trim cooler, dehydrated and compressed in an intercooled compressor to the final pressure as specified in the design basis. Stream data for this subsystem are presented Table 3-13.

Table 3-10
Coal Gasification based ZEPP Cycle
Overall Plant Performance Summary
Full Quench versus Partial Quench Gasifier Cases

Gasifier Heat Recovery	Full Quench	Partial Quench
Coal Feed Rate, ST/D (MF)	1,679	1,610
MMBtu/hr (HHV)	1,672	1,604
MMBtu/hr (LHV)	1,616	1,550
Coal Feed Rate, MT/D (MF)	1,523	1,461
GJ/hr (HHV)	1,764	1,692
GJ/hr (LHV)	1,705	1,635
Natural Gas		
MMBtu/hr (HHV)	18	17
MMBtu/hr (LHV)	16	15
GJ/hr (HHV)	19	18
GJ/hr (LHV)	17	16
Power Generation, kWe		
Gas Turbine	168,855	175,478
Steam Turbine	4,464	35
ORC Turbine	18,890	20,595
Syngas Expander	2,961	2,921
Total Power Generated	195,170	199,030
Auxiliary Power Consumption, kWe	73,965	70,907
Net Plant Output, kWe	121,204	128,123
Generation Efficiency (HHV)		
Net Heat Rate, Btu/kWh	13,943	12,652
Net Heat Rate, kJ/kWh	14,707	13,346
% Fuel to Power	24.48	26.98
Generation Efficiency (LHV)		
Net Heat Rate, Btu/kWh	13,465	12,219
Net Heat Rate, kJ/kWh	14,203	12,889
% Fuel to Power	25.35	27.93

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Table 3-11
Coal Gasification based ZEPP Cycle
Gas Turbine Losses
Full Quench versus Partial Quench Gasifier Cases

Gasifier Heat Recovery	Full Quench		Partial Quench	
Turbine	Net Output, kWe	Mech & Gen Losses, kWe	Net Output, kWe	Mech & Gen Losses, kWe
High Pressure	39,598	808	45,121	921
SGT-900	129,257	2638	130,357	2660
Total Gas Turbine	168,855	3446	175,478	3581

Table 3-12
Coal Gasification based ZEPP Cycle
Balance of Plant Power Consumption
Full Quench versus Partial Quench Gasifier Cases

Gasifier Heat Recovery	Full Quench	Partial Quench
	kWe	kWe
Coal Handling, Milling and Drying	2,214	2,124
Gasifier System	1,576	1,319
Air Separation Unit	40,032	38,374
Syngas Compressor	2,288	2,143
CO2 Compressor	18,681	17,919
Warm Gas Cleanup & H2SO4 Unit	2,551	2,453
BFW and Steam Condensate Pumps	1,655	1,777
Cooling Tower Fans and Pumps	4,227	4,048
Gas Turbine Auxiliaries	275	285
Steam Turbine Auxiliaries	15	0
ORC Turbine Auxiliaries	28	31
General Makeup and Demineralized Water	2	2
Transformer Losses	423	431
Total Auxiliary Power Consumption	73,965	70,907

Table 3-13 Coal Gasification based ZEPP Cycle Stream Data Partial Quench Gasifier Overall Block Diagrams (BFD-004, 005 & 006) - 96.5% O ₂ Purity Case															
BFD Stream No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Temperature C	15	26.7		11.1	27	350	40	305.1	60	442.5	27	15	495.6	143.9	11.1
Pressure bar	1.014	60.66	1.014	48.346	61.655	48	49	92.25	1.014	41.311	61.655	1.014	35.832	42.413	1.393
Vapor Frac	Solid (As Received)	1.00E+00	Solid	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	Solid (Dry Basis)	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00
Mole Flow kmol/hr		270.9204		1380.139	243.1456	560.1619	18.56945	5012.371		6965.219	112.0333	662.5679	7069.88	8.26366	54.3807
Mass Flow kg/hr	66,129	7589.425	61,795	44382.05	10604.42	10091.48	318.8685	90299.27	10,222.41	143127.6	4886.162	19117.89	146400.1	231.4896	1748.759
Component Mole Flow kmol/hr															
O2		0		1331.836	0.001711	0	0	0		0	0.000684	137.6154	0.000684	0	52.47749
N2		270.9204		13.80117	4.290944	0	0.118737	0		40.15728	1.977119	511.6348	42.13474	8.26366	0.543725
AR		0		34.50172	6.821711	0	0	0		41.32343	3.14327	6.228028	44.4667	0	1.359483
H2		0		0	0	0	0	0		1497.083	0	0	1497.083	0	0
CO		0		0	0	0	0	0		3274.301	0	0	3274.301	0	0
CO2		0		0	232.0313	0	0.241237	0		228.9143	106.9123	0.198807	340.9757	0	0
H2O		0		0	0	560.1619	0	5012.371		1783.29	0	6.890832	1870.073	0	0
CH4		0		0	0	0	17.4998	0		0.789411	0	0	0.789411	0	0
H2S		0		0	0	0	0	0		86.82865	0	0	0.044826	0	0
NH3		0		0	0	0	0	0		6.501088	0	0	0	0	0
COS		0		0	0	0	0	0		4.960591	0	0	0.010265	0	0
HCl		0		0	0	0	0	0		0.941339	0	0	0	0	0
HCN		0		0	0	0	0	0		0.127633	0	0	0	0	0
SO2		0		0	0	0	0	0		0	0	0	0	0	0
C2H6		0		0	0	0	0.545778	0		0	0	0	0	0	0
C3H8		0		0	0	0	0.124554	0		0	0	0	0	0	0
C4H10-01		0		0	0	0	0.039009	0		0	0	0	0	0	0
C5H12-01		0		0	0	0	0	0		0	0	0	0	0	0
H2SO4		0		0	0	0	0	0		0	0	0	0	0	0

[illegible]

[illegible]

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Conclusions and Recommendations

As seen from data presented in Table 3-6, the overall plant performance is slightly better for the 96.5% O₂ purity case over the 99.6% O₂ purity case while capital cost savings should be realized in the lower O₂ purity case.

From data presented in Tables 3-2 and 3-7 or 3-11, it may be seen that the power outputs of the HP and the IP turbines for the coal gasification based cases are significantly lower than those for the natural gas fired cases. As mentioned previously, the mass flow rate of the gases leaving the IP turbine was held constant for all cases while the difference in the relative amounts of CO₂ and H₂O vapor in this stream causes the power output to differ for the two set of cases. The power output of these turbines is almost proportional to the molar flow rate of the gases exhausting the turbines which is to be expected since the molar specific heats of CO₂ and H₂O vapor are similar, both being tri-atomic gases. A detailed analysis of the IP turbine aerodynamics is required to establish the scale factor accurately for these cases.

As seen from data presented in Table 3-10 and as expected, the overall plant performance is significantly better for the Partial Quench Gasifier Case over the Full Quench Gasifier Case, the heat rate being reduced by as much as 9%. Capital cost of the Partial Quench Gasifier Case on a tonne/hr of coal gasified is expected to be higher because of the cost of the radiant cooler. Plant costs for the two cases should be developed and an economic analysis performed in order to quantify the overall advantage of the partial quench design.

In the coal based plant, the gasifier operating pressure is significantly lower than the HP combustor pressure which requires cooling and compression of the syngas before it is supplied to the HP combustor. The cooling operation which condenses out the H₂O vapor introduces a significant penalty to the thermal efficiency of the plant and this cooling /compression step may be avoided if the gasifier operating pressure and the HP combustor pressure are made compatible, either by increasing the gasifier pressure and/or decreasing the HP combustor pressure (and the HP turbine pressure ratio).