**Advanced Turbine System (ATS)
Task 1 -- System Scoping and Feasibility Study**

Final Report

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ABSTRACT

The DOE-ATS Design Program Task 1 is for System Scoping and Feasibility Studies with the following subtasks:

1.1 Selection of Natural Gas-Fired Reference System

1.2 Description of Natural Gas-Fired Reference System

1.3 Conversion to Coal-Fueled Reference System

Present GT(Gas Turbine) Systems are available to achieve 52% (LHV) thermal efficiencies, plants in construction will be capable of 54%, and the goal of this study is to identify incentives, technical issues, and resource requirements to develop natural gas- and coal-compatible ATS which would have a goal of 60% or greater based on LHV.

The prime objective of this project task is to select a natural gas-fired ATS (Advanced Turbine System) that could be manufactured and marketed should development costs not be at issue with the goals of:

- Cost of electricity 10% below 1991 vintage power plants in same market class and size
- Expected performance 60% efficiency and higher
- Emission levels

NO _x	< 10 ppm (0.15 lb/MW-h)
CO	< 20 ppm (0.30 lb/MW-h)
UHC	< 20 ppm (0.30 lb/MW-h)

- Selection of most marketable coal fuel system beyond 2005

ABB screening studies have identified the gas-fueled combined cycle as the most promising full scale solution to achieve the set goals for 1998-2002. This conclusion is based on ABB's experience level, as well as the multi-step potential of the combined cycle process to improve in many components without introducing radical changes that might increase costs and lower RAM.

The technical approach to achieve 60% or better thermal efficiency will include increased turbine inlet temperatures, compressor intercooling, as well as improvements in material, turbine cooling technology and the steam turbine.

- Use of improved component efficiencies will achieve gas-fired cycle performance of 61.78%
- Conversion to coal-firing will result in system performance of 52.17%.

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**ADVANCED TURBINE SYSTEMS (ATS)
DOE-ATS: DE-AC21-92MC29234**

TASK 1 – SYSTEM SCOPING AND FEASIBILITY STUDIES

FINAL TECHNICAL REPORT

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1. INTRODUCTION

Present gas turbine based systems are available to achieve thermal efficiencies of 52%-54%. The need for even higher efficiencies in the future, along with low emissions and low operating costs, is apparent and has resulted in programs which are categorized as Advanced Turbine Systems (ATS).

The prime objective of this project task is to select a natural gas fired ATS capable of reaching 60% cycle efficiency. Several cycles were compared and evaluated under all different kind of aspects, to determine the one with the highest potential and, at the same time, the best overall fit within an experience base to guarantee project goals.

The goals and objectives set for the Advanced Turbine Systems can only be achieved with the introduction of new technology features. Based on ABB's experience over the last 50 years with combustion turbine technology, it was decided that the multi-step development potential of an advanced gas turbine in a combined cycle would offer a great opportunity to achieve major improvements over the current technology. The two main reasons for such an approach are based on the following milestones:

- Introduction of gas turbines

The principles were developed in the 30's or even earlier, and the first unit was realized in 1939. The real industrial introduction was achieved in the 50's.

- Introduction of CC technology

The thermodynamics were developed in the 50's and the industrial realization was achieved in the early 70's.

ABB concluded that a careful investigation of the current technology in combination with the potential of advanced features will result in an advanced combustion turbine plant which could achieve the efficiency and emissions target, as well as fulfilling the RAM requirements and the cost requirements. The results of this investigation will be discussed in this report. The combined cycle plant, with a state-of-the-art HRSG and steam turbine built around an advanced combustion gas turbine with a firing temperature of approximately 2600°F (1450°C), can achieve all of the set goals.

Major improvements aim at increasing the turbine inlet temperature to levels above 2600°F (1450°C) and at improving the cooling of the turbine section. Innovative cooling technology for turbine blades and vanes will be the answer to the high hot gas temperature. This was investigated by ABB in the early '80s and resulted in a steam cooling of the complete turbine in a closed loop system (U.S. Patent 4,424,668-1984). During this investigation, it was determined that several development steps would be needed for a closed loop steam cooling design for the rotor. After investigating the different options, closed cycle steam cooling was chosen for the cooling of turbine vanes and the vane carrier, whereas the rotor and the turbine blades will be cooled by air. Major development areas have been identified in both areas which will result in - significant changes in turbine design.

The technical basis for this project phase will be an already existing gas turbine with all development steps clearly outlined in the context of this machine. This approach will make it easier to define new development areas, as well as making it possible to evaluate the individual steps for achieving the overall goal of thermal efficiencies of 60% or greater.

Low emissions are a second objective within the project scope and they have to be achieved without the use of post combustion exhaust gas treatment, such as Selective Catalytic Reduction (SCR). Lean premix combustion technology was identified for reaching this goal and substantial in-house experience is available to define a development plan for reaching this goal. Again, the challenge will be to increase the turbine inlet temperature and at the same time, to keep the emissions at levels associated with much lower firing temperatures.

Finally, the question of new materials is raised. Advanced turbine systems with firing temperatures above 2600°F will require new materials and the associated development needs have to be clearly defined. This goal will be closely connected to the cooling technology for turbine rotor and stator.

The combination of all of the items mentioned above will determine operating and capital cost, as well as items like reliability, availability and maintainability (RAM). Since this study is based on an existing turbine system with multi-step improvements, the level of confidence in defining the necessary outlines is rather high and well founded, which makes the target date for the overall ATS program more easily achievable.

2. PURPOSE

The project purpose was to perform System Scoping and Feasibility Studies for Advanced Turbine Systems (ATS) and includes the selection and description of a natural-gas-fired reference case, as well as the identification of a coal-fired system which is to use the gas turbine from the natural-gas-fired reference case. The following requirements were defined:

Thermal Efficiency

$$\eta_{\text{thermal}} = 60\%$$

The thermal efficiency shall be greater than 60%.

Cost of Electricity.

$$C_{EL} = 0.9 \times C_{EL\ 1991}$$

The cost of electricity shall be 10% below 1991 vintage power plants.

Emissions.

$$\begin{aligned} \varepsilon_{\text{NO}_x} &< 10 \text{ ppm} \\ \varepsilon_{\text{CO}} &< 20 \text{ ppm} \\ \varepsilon_{\text{UHC}} &< 20 \text{ ppm} \end{aligned}$$

All emission targets have to be met without any post-combustion emissions control devices.

RAM. Reliability, Availability and Maintainability (RAM) shall compare to today's systems.

Issues:

- High RAM
- High Efficiency
- Low Emissions

Figure 1 Goals - Predicted Trends for ATS Program

Figure 1 shows the goals, as well as the trends for emissions, cycle efficiency and RAM combined in one graph. It is apparent that only the thermal efficiency goal coincides with the behavior of a gas turbine based plant, when the turbine inlet temperature is increased. The emissions and the RAM issues tend to increase with higher temperatures. This conflict was analyzed at any early point in a way that made using a well known equipment basis for this project more than an asset, but a necessity to reach all three goals to the same extent.

A further purpose of the study is to look at how such an ATS cycle would be commercialized, as well as examine the market potential for the specific system size that would be scoped.

3. BACKGROUND

The work done in this study (ATS-Task 1) shows clearly that ABB's multi-step approach has the potential for achieving 60% cycle efficiency, while limiting the emissions to 10 ppm NO_x and 10 ppm for CO and UHC. Present ABB gas turbine plants already achieve cycle efficiencies of 54% at corresponding turbine inlet temperatures of 2300°F (Inlet of 1. Stage Turbine Vane). NO_x emissions of less than 10 ppm have been measured in the 80 MW gas turbine of the type GT11N, with CO and UHC emissions of less than 10 ppm in the Midland Cogeneration Venture facility in Midland, Michigan.

The main performance variables are identified as turbine inlet temperature and turbine polytropic efficiency. Performance calculations have shown that turbine inlet temperatures above 2600°F have to be considered for reaching the required goals. This key temperatures will then drive the other thermodynamic variables, such as exhaust gas temperature, compressor pressure ratio and, finally, the thermal efficiency. The interdependence of compressor pressure ratio, exhaust gas temperature and thermal efficiency was investigated, since only the combination of high gas turbine efficiency and high turbine exhaust gas temperature will result in a successful application. Exhaust gas temperatures of up to 660°C (1200°F) and gas turbine efficiency of about 37% are required for an optimized steam bottoming cycle and a high overall cycle efficiency.

Figure 2 Water/Steam Cycle - Two Main Categories

A variety of different water/steam cycles are available for optimizing the thermal efficiency of a gas turbine based power plant. Figure 2 shows the most important cycles, divided into two main categories with the gas and steam either separated or mixed. Any configuration in which water or steam is mixed with the hot gases from the turbine have the potential for high thermal efficiencies. However, the combined cycle, with hot gases and steam separated, has several advantages:

1. High efficiencies of more than 54% have been already reached (based on GT 13E2) with rather low firing temperatures of 2160°F (ANSI).
2. Proven components can be used for further development at higher firing temperatures.
3. High multi-step development potential.
4. Optimum expansion possibilities in future including integration of coal-firing.
5. Minimum water consumption with potential of dry combustion.

Figure 3 ATS Multi-step Development Potential of Combined Cycle

Figure 3 shows a quantitative presentation of how to reach the goal of 60% thermal efficiency. The reference curve at the bottom is based on already existing ABB technology. Two points, at 52% and 54% efficiency have been determined in two projects, PEGUS12 in the Netherlands and DEESIDE in the U.K. The multi-step development curves utilize improvements of the different components in a combined cycle, such as turbine cooling technology, compressor inter-cooling and state-of-the-art heat recovery steam generator and steam turbine. The performance projections will determine which of these improvements will be incorporated in the cycle configuration.

4. RESULTS AND DISCUSSIONS REFERENCE CYCLE - COMBINED CYCLE GT WITH CLOSED CYCLE STEAM COOLING (CCSC)

4.1 GAS TURBINE

Reducing the cooling air requirements for the hot gas components in the turbine section has been an ongoing process, since the turbine inlet temperatures have been increasing steadily. The two main reasons are the loss in gas turbine efficiency and the loss of air otherwise available for lean-premix combustion technology. Any air used for cooling the rotating and stationary parts in the turbine section, will not be expanded to its optimum and will therefore be associated with a decrease in efficiency.

Turbine Cooling Technology. Using today's cooling technology, the increase of the turbine inlet temperature up to 1430°C (2600°F), would result in a very high air mass flow for cooling and, subsequently, in a high penalty on the efficiency rating. After looking at the different options, it was decided to use closed cycle steam cooling (CCSC) for the stationary part of the turbine and advanced air cooling technology for the rotating components in the turbine section. CCSC has been recognized as an attractive option for quite some time and ABB has contributed to the technology with their own research and some new development features which resulted in a patent on blade cooling.

Hence, ABB is proposing the steam cooling of the stator, vanes, stator casing, combustor, etc., i.e. all stationary parts, where it is easy to seal and the steam (after cooling the GT components) can be introduced in the steam turbine.

The amount of cooling air required is significantly lower, since only the rotor and the turbine blades are air cooled. The advantage is manifold: In an air-cooled turbine the cooling air is compressed in the compressor and cools the vanes/blades, rotor, combustor, etc. and picks up considerable heat. The expansion of this air in the turbine is, however, poor. The difference between work received due to expansion and work needed to compress the air is usually negative, as the cooling air expands at significantly lower pressure. This loss is called throttle loss which is approximately 2% of the turbine efficiency, resulting in around 5% gain in thermal efficiency (multiplicative). Besides, the introduction of closed cycle steam cooling of the stator vanes avoids the mixing losses of coolant and the hot flow from the film cooling in the flow passages and in the trailing edge area of the cooled vanes. There is also an increase in polytropic efficiency of the vanes/blades, as the expansion is taking place as non-adiabatic. In total, these effects should result in approximately 8% (multiplicative) improvement in thermal efficiency of the gas turbine.

Another improvement can be seen in the steam cycle, as the steam temperature is increased during cooling of the gas turbine, resulting in a reheat effect. The total heat introduced in the steam leads to an increase in steam turbine output and hence, the efficiency of the total cycle. For a combined cycle plant, this improvement should result in an improvement of 10% (multiplicative) or more for the combined cycle efficiency.

The new technology connected to this feature evolves around the vane cooling path design which needs to be very effective over the complete surface of the vane. Especially the trailing edge area and proper design of the vane (thin-walled design) with mechanical and thermal integrity, needs attention and has to be tested carefully.

This new feature introduces at the same time some operationally new aspects. During start-up, when no steam is available, these vanes will be cooled with air. This design will show that the gas turbine can be started independently, and that the commissioning process should not be more difficult than it is today.

Lean-Premix Combustion. One of the main goals of the ATS project is the limitation of emissions from the gas turbine without the use of post-combustion emissions control devices. The requirements for advanced turbine systems include high gas turbine firing temperatures and low emissions, with both items strongly affecting the combustor technology. ABB has extensive experience in a wide range of different combustor designs and combustion processes. State-of-the-art premix burners in various arrangements are available with a proven record of low emissions and high reliability. Early on, ABB decided to utilize a combustion technology which is known in the industry as lean-premix. ABB introduced their first generation lean-premix burners in 1984 and has continuously worked on improving this combustion technology towards lower emissions as well as an inherently safer design, resulting in the second generation lean-premix, the EV burner. This dry low NO_x burner consists of two half cones which are designed in a way that the flame is stabilized by vortex break-down in free space in a premix mode, without the requirements of a mechanical flame holder, such as a swirler. Following two years of intensive laboratory work with very promising results, the double cone EV burner (Figure 4) was successfully installed in an already existing gas turbine, a GT11N. During the commissioning phase, the burner has, with a turbine inlet temperature of 2150°F, proven that the emission limits of 10 ppm NO_x can be achieved. Figure 5 shows NO_x measurements from high-pressure (HP) lab tests, as well as actual field data (GT11N).

Figure 4 Dual-Fuel Double-cone Burner

GT11N-EV <--> High pressure tests

Figure 5 Comparison NOx Emissions

This technology results in a flame which is much colder than the traditional diffusion flame. Since the production of thermal NOx is mainly influenced by flame temperature, it has been shown that NOx levels of less than 10 ppm can be reached at current turbine inlet temperatures. The flame temperature of the lean-premix system is approximately 1540°C (2800°F) and is typically reduced down to 2100 to 2300°F at the turbine inlet by mixing it with cooler compressor discharge air. By reducing the cooling air requirements of all the hot gas components, the flame temperature will further decrease and the turbine inlet temperature will approach this new flame temperature. Therefore, it is expected to reach turbine inlet temperatures as high as 1,450°C (2,640°F) without increasing the emissions. However, one other factor for NOx production is the pressure at which combustion is taking place, and we will have to investigate how compressor pressure ratios of 16 to 17 will influence the emissions.

4.1.1 COMPRESSOR INTERCOOLING

The concept of compressor intercooling is well known and is used to reduce the work of compression, resulting in an overall increase in gas turbine power output. However, since the compressor discharge temperature is also reduced, more heat input into the combustor is necessary to reach a certain firing temperature.

During our investigation of an intercooled gas turbine within a combined cycle, the main problem was identified in the low quality of the heat available, when cooling the

compressor air after 1/3 of the compressor pressure ratio has been reached. Since the air temperature at that compressor stage is only approximately 150°C (300°F), it can not be used for the steam cycle. Instead, the only possible application seems to be in utilizing the heat for fuel preheating. However, it was easily determined that the heat generated from the compressor inter-cooling is too large to be absorbed by the relatively small fuel preheater.

One future application for a compressor intercooler within this ATS project could be its benefit for generating lower temperatures at the compressor discharge. This could become an advantage when looking at the optimum cooling air requirements for the gas turbine rotor. It has to be determined in a later phase, whether this is the case.

4.2 HEAT RECOVERY STEAM GENERATOR (HRSG)

Recent trends in the application of combustion turbines for power generation indicate that large-frame machines in the size range from 80 MW to 250 MW will be used for utility combined cycle applications. A growth of combined cycle technology is also taking place with utilization of steam cycles with higher steam pressure and temperatures, reheat cycles and steam induction for power augmentation in the steam turbine at intermediate and low pressure levels. These steam cycle characteristics promote the maximum utilization of gas turbine exhaust heat energy, using proven boiler and turbine technologies. The components supplied by the boiler manufacturer for a Heat Recovery Steam Generator (HRSG) are typically supplied as prefabricated subassemblies. The most advanced combined cycle configuration of today is based on a three-pressure, reheat heat recovery steam generator (HRSG). Figure 6 shows a typical example of such a configuration.

Figure 6 3-Pressure Heat Recovery Steam Generator

The arrangement of heat exchanger sections for multiple pressure levels are arranged to take maximum advantage of temperature differences between exhaust gas and tube side temperatures. The HRSG can be arranged for horizontal gas flow across vertical tubes or vertical gas flow across horizontal tubes. Pressure parts are enclosed in an internally insulated casing and are completely free to expand independently of the outer casing structure. The major changes for the ATS program will be on the material side, which is typically designed for gas turbine exhaust gas temperatures of less than 580°C (1076°F). For advanced turbine systems these temperatures will be as high as 660°C (1220°F) and will result in steam temperature of up to 620°C (1148°F). It is apparent that the choice of materials will concentrate on austenetic steels.

All elements of the inlet duct and the HRSG casing employ a cold outer casing concept. This casing, which acts as the pressure boundary for exhaust gases, is completely welded and is isolated from high temperature gas by an extensive internal insulation system. A system of internal liner plates protects the insulation from gas flow. The liner system is made of many well-supported plate segments that are overlapped in the direction of gas flow. This approach to casing design permits the development of large structures that are free from the effects of differential thermal expansion during start-up and in service.

Similarly, the heat exchanger tubing employs extended surfaces on all tubes to maximize the heat transfer surface. This tubing is rugged and field proven over many years and can be reliably utilized in the present ATS program.

The two critical temperature differences that influence the amount of heat-transfer surface and the overall steam generated at each pressure level are the:

- Pinch points: The difference between the gas temperature leaving an evaporating section and the temperature at which boiling is occurring (saturated water temperature).
- Approach temperature: The difference between the saturated water temperature in an evaporating section and the incoming feedwater temperature.

The pinch point strongly influences the amounts of heat transfer surface in the evaporating section. Current HRSG designs use pinch points in the 15 to 25°F (8 to 14°C) range. In general, these boilers have 50% more surface in the evaporating section than boilers with pinch points of 40 to 50°F.

The approach temperature also influences the amount of surface required for an economizer section, with exponentially increasing amounts required for very low approach temperatures. Current HRSG economizers have approach temperatures in the 15 to 25°F range at the design point. Many other operating conditions can occur at off-design points, including start-up. Some conditions will result in steaming at the exit of the economizer, such that it acts as an evaporative surface.

Specific provisions to accommodate steaming at levels up to 5% of total flow in an economizer include: 1) careful control of water distribution in the last downflow passes of the economizer to cause that portion of the economizer to behave as a force-

circulation evaporator, or 2) configuring the last few passes of the economizer as entirely up-flow with relief by natural circulation into the steam drum.

This highest steam cycle conditions, with extended operating experience, are at Unit 1 of the Eddystone Station in Philadelphia. This ABB unit was designed for coal firing with super heater outlet conditions of 5000 psi and 1200°F (648°C). The unit started operation forty years ago and is now operating at 4500 psi and 1135°F (613°C), which is comparable to our proposed steam temperature of 1145°F (618°C). Therefore, the materials and technology to design and build the high temperature sections of the proposed HRSG are proven and no major R&D is required.

Fuel preheating will be part of the cycle configuration. Low pressure steam will be taken to a fuel/steam heat exchanger. Figure 7 shows a typical example of a process flow diagram for a three pressure, re-heat boiler, including fuel preheating and CCSC for the gas turbine.

Figure 7 **ATS Process Flow Diagram**

4.3 STEAM TURBINE

A reheat steam turbine, divided in high, intermediate and low pressure section was chosen for this project. The isotropic efficiencies of the different sections are approximately 91 to 92%. Figure 8 shows a typical cross section of such a steam turbine. This machine is from ABB's compact MT series and has the following design features:

- HP and IP-LP turbines in separate casings for a double casing reheat turbine
- Orientation of turbine that torque is balanced
- LP turbine with axial exhaust for optimum flow conditions with minimum losses
- Designed for fast start-up and fast load changes
- No pre-heater for minimum losses in stack
- The three pressure levels result in corresponding pressure for Closed Cycle Steam Cooling (CCSC) system
- Integration expansion sleeve coupling
- Reaction type blading 8000 according with optimized aerodynamic design for high polytropic efficiencies
- The integration of the reheat steam from the gas turbine in the steam turbine design

Figure 8 Compact Reheat Steam Turbine with Axial Exhaust (KA13 E2-1)

Recently, ABB has designed and developed new blading for the high pressure part of the steam turbine. This blading includes 3D features such as compound lean of the trailing edge region to reduce secondary flows and boost efficiency. Scale model tests on a five stage machine indicate that this blading has an aerodynamic efficiency gain of more than one percent. The blading is currently introduced into the ABB compact steam turbines and will be made available to the ATS program. Since all components of the ST are proven, there is no requirements for R&D.

4.4 COMBINED CYCLE CALCULATIONS

4.4.1 PEGUS12 - REFERENCE CASE

Within the framework of the DOE-ATS Feasibility Study, ABB has decided to utilize a combined cycle based on the multi-step development potential and the existing experience level. However, it is important to integrate this advanced gas turbine (AGT), together with a heat recovery steam generator (HRSG) and a steam turbine (ST) for maximum efficiency.

The PEGUS12 plant is a combined cycle power plant in the Netherlands with a thermal efficiency of 52% based on a GT 13E gas turbine, a two pressure boiler and a reheat steam turbine. This cycle was used to evaluate the several cycle programs, i.e. GATE/ CYCLE, ASPEN PLUS etc. which are available in-house. The comparison clearly showed that each of the packages has the capability of modeling such an application. It was decided to proceed with ASPEN, since it will allow for future integration of special applications.

In a closed steam cycle available energies are transferred from one component to the next component in the cycle except at the energy rejecting point across the system boundary. Inside the cycle, the available energy degrades it's efficiency due to the various heat losses, pressure losses, mechanical losses, differences in the gas and steam temperature in the HRSG, and limitations in steam expansion due to condenser pressure. The rejected energy includes: energy losses from the HRSG exhaust stack, the energy from steam dumping to condenser, and leakage of energy to the surroundings. Using the ASPEN program, several cycles were modeled with the improved GT13E2 as the technology base to build upon.

4.4.2 EFFECT OF COMPONENT IMPROVEMENT

Reference Case. The basis for this section of the investigation is the ABB gas turbine GT 13E2, with annular dry low NO_x combustor (see Figure 9). The GT 13E2 has a compressor which is both axially and radially split for easy machining and maintenance. The rotor follows traditional ABB design with a welded rotor. The GT 13E2 is designed for the 50 Hz market, but its technology can be scaled down for a 60 Hz machine with a similar efficiency by applying a factor of 1.2² for power output and mass flows. ABB has developed axial compressor technology over the last 50 years. These compressors now have polytropic efficiencies of about 91%. Currently, the computer codes used in the design process have been extensively validated by test rig results and from results in the open literature, and ABB has good confidence in the design methodology used for compressor design.

Figure 9 GT13E2 Thermal Block

The main work done here was to establish that the compressor operating conditions will allow for the extra mass flow availability by the reduction of cooling air requirement for the turbine. Besides, the operating point due to lower turbine mass flow leading to reduced pressure ratio needs to be defined in the compressor map.

Due to the reduction in cooling air requirement from the turbine, achieved by steam cooling and advanced air cooling, there will be more mass flow through the compressor and less mass flow through the turbine. This is because intermediate pressure cooling air for the low pressure turbine cooling (drawn from the 5-7th stage of a 15 stage compressor) will be significantly reduced.

ABB is currently involved in upgrading its family of Axial Compressors for its new range of engines. However, the basis for the compressor aerodynamic performance for the ATS will be that of the recently launched GT13E2 Gas Turbine Plant. The advances to be made in future compressors will be mainly that of reducing the number of stages while maintaining or improving the present component efficiencies. It is considered that by 1996, the improvement in Compressor Aerodynamics will yield around 0.5 to 1.0 point in efficiency gain.

This is not part of the ATS program, but will enhance the final ATS machine at entry-into-service for the year 2002. The ability to achieve the same, or better, compressor performance with fewer parts count will result in a machine with superior RAM qualities, lower cost and higher GT cycle efficiency.

Advanced Turbine Technology

ABB has been developing turbines over the last 50 years and are now poised to make significant improvements to the overall turbine efficiencies. Current turbines operate at around 84-85% in-engine cooled polytropic efficiency, including all throttle and mixing losses. ABB is already developing advanced turbine components which will increase this by around two points in efficiency. These turbines will be evolved around the GT13E2, GT11N2 type of "family" turbines and do not take into account any significant reductions in cooling air mass flow. Final cycle adjustment for approximately 62% efficiency uses 88% polytropic efficiency.

It is considered that within the time frame for the present ATS program, these new turbines will be available well before the engine-in-service date of year 2002. The development of the ATS is therefore considered to be a low risk item in terms of meeting the overall GT cycle efficiency.

The turbine used for the ATS will be that of the GT13E2 gas turbine or an upgrade thereof. This turbine is well proven and requires little change to meet the performance requirement for the ATS. However, as stated above, ABB is committed to improving turbine aerodynamic performance as part of another internal program of work alongside the present DOE/ATS program. Such a change will ensure that any new turbine will be able to comfortably meet or exceed the present performance of the GT13E2 turbine module with superior RAM features.

Cooling Effectiveness

Preliminary calculations indicate that the cooling effectiveness will be increased by approximately 25% when using steam instead of air at the same conditions. This indicates the relative merit (Figure 10) of using steam cooling. Further work will have to be carried out in this area where the steam is introduced at the optimized HRSG delivery conditions which will be at higher pressure and lower temperature. These

conditions will be beneficial for the cooling design because the Reynolds number of the cooling steam will be higher and makes for higher cooling efficiency. The actual cooling effectiveness and the cooling efficiency for the steam cooled part will have to be established and fixed on the cooling technology charts, Figure 10.

Figure 10 Non-Dimensional Cooling Performance for Stator Vanes

Steam Cooled Vane Carrier

The vane carrier plays an important role in supplying the cooling medium (air or steam) to the cooled component (vane or heat shield). In ABB GT units it has been the case that the vane carrier and the heat shields are also cooled by the air passing through them prior to entering the vanes. In the present case, some complexity is involved because there needs to be a segregation between the steam and the air cooling media.

The vane shrouds will be extended to eliminate the heat shields. Sealing strips between the shrouds will be installed. Minor air cooling will be used to cool the seals and to avoid damage by hot gas ingestion into the vane carrier.

Air Cooled Rotor Blade Components

The technology difference between utility and aircraft engine cooling system effectiveness and efficiency is shown on Figure 11. The goal for the air cooled parts for the ATS program lies between the two technologies and therefore it is clear that there needs to be a migration upwards for the utility machines to meet the requirements of the ATS program. This is considered to be a low risk development because the aircraft engine technology can already comfortably exceed the cooling targets. However, work will need to be done in transferring the highly complex aircraft cooling systems into the utility size components.

Figure 11 Non-Dimensional Cooling Performance for Rotor Blades

ABB has already introduced an aggressive program of work (1990) to improve the cooling performance of air cooled vanes and blades. This is done by a two step approach whereby the cooling system efficiency is improved while, at the same time, advanced materials technology is introduced. It is expected that this will result in turbines operating at 2750°F by the end of the century. It is considered that this is a realistic goal, because modern aircraft engine designs can already operate at these temperatures.

Table 1 shows the reference case with a gas turbine power output of 114.0 MW and a thermal efficiency of 35.7%. This reference case was then calculated in the combined cycle model, where it gave a cycle efficiency of 54.51%.

Closed Cycle Steam Cooling (CCSC1).

For the next step, the stator cooling was shut-off, while the temperature in front of the first turbine vane is kept constant at 1243°C (2269°F). Heat was extracted from the gas turbine and was transferred into the steam which was then dumped into the IP section of the steam turbine. This resulted in an increased efficiency of the gas turbine to 36.72%, with an approximately constant exhaust gas temperature. The corresponding cycle efficiency was calculated to be 56.43%.

Increased Turbine Inlet Temperature (CCSC2).

Increasing the inlet temperature to 1350°C (2462°F) resulted in an increase in pressure ratio from 15.0 to 17.2 and it was decided to open the first turbine vane to reduce the pressure ratio down to its original value. After turning the vanes -7°, the exhaust gas temperature changed to 620°C and the GT efficiency dropped to 35.92%. The cycle efficiency for this case was determined as 58.19%.

Increased Turbine Inlet Temperature (CCSC3).

This case was calculated with a turbine inlet temperature of 1454°C (2650°F). The 1. turbine vane was opened by 1°, since the exhaust gas temperature would have otherwise exceeded the limit of 660°C (1220°F). The corresponding pressure ratio increased to 17:1, and the GT efficiency was determined as 36.97%. The cycle efficiency for this case resulted in 60.03%.

Improved Component Efficiency (CCSC4).

Table 1 includes a summary of the performance variables. A more detailed analysis of the gas turbine cooling system and improvements in polytropic compressor and turbine efficiency lead to a leap in GT thermal efficiency from approximately 37% to 40%. Cooling air flow rates for the rotor were reduced to reflect advanced cooling technology. At the same time, all other GT components, i.e. exhaust gas diffuser were improved, to show impact of advanced technology. The table below shows the values which were presented at the HEAT ENGINE CONFERENCE in Morgantown, as well as the recalculated data. The cycle efficiency increased to 61.78%, which shows a substantial increase over the 60.03% presented in October, 1992.

CASE	Te1 C	Te1 F	T exh C	T exh F	P ST MW	P GT MW	ST/GT	GT ETA %	CC ETA %
BASE	1243	2269	525.0	977	60.28	114.0	0.53	35.70	54.51
CCSC1	1243	2269	526.1	979	67.68	127.0	0.53	36.72	56.43
CCSC2	1350	2462	620.0	1148	91.45	147.2	0.62	35.92	58.19
CCSC3	1454	2650	660.0	1220	105.00	165.3	0.64	36.97	60.03
CCSC4*	1454	2650	657.0	1215	99.95	181.9	0.54	40.07	61.87

- 1) Turbine Inlet Temperature defined at Inlet of 1. Turbine Vane
- 2) Steam Power Output includes 3MW of Auxiliary Loads
- 3) Cases "CCSC 1-4" are with Closed Cycle Steam Cooling
- *) Based on improvements on the GT Cooling System

Table 1 Combined Cycle Performance

5. IDENTIFICATION OF INTERMEDIATE DEVELOPMENT NEEDS

The multi-step development project proposal of ABB requires, amongst others, the introduction of advanced high temperature materials and advanced steam cooling concepts. The high temperature materials will be needed to raise the turbine inlet temperature (TIT) and to reduce the requirements for cooling air in the combustor. A future dramatic increase of TIT will be possible by the use of steam cooling.

In addition to the selection of appropriate materials to meet the service stress/strain/environment/life requirements of the component system, the manufacturing technology associated with the specific processing route, and quality control system, must be selected to assure cost effective solutions to the system integrity and life requirements.

ABB has significant experience in optimizing the materials technologies for steam and combustion turbine systems, to meet market needs. ABB has developed proprietary alloy and coating compositions to meet the unique demands of the power generation systems. An integrated program of research and development continues at ABB's international facilities in the USA, Germany, Sweden and Switzerland. In general support of this program, independently funded activities are underway in the following research topics:

- Corrosion-resistant, high-castability, directionally-solidified and single-crystal alloys.
- Casting process science for directionally-solidified and single-crystal blading.
- Optimization of blading design for high casting-yield by process simulation modeling.
- Improved reliability, high temperature oxidation/corrosion protection coatings.
- Improved bond coatings for thermal barrier coatings.
- Ceramic systems for lightly loaded combustor components.
- Power metallurgical manufacture of large steam turbine blades.
- Lightweight blading for intermediate temperatures.

The output from these programs, in terms of developed materials and processes, will be used in further development of the ATS program.

The unique material solutions required to meet the innovative power-generation cycles will require demonstration/validation. Thus, while improved temperature capability combustor and turbine materials will be made available from the ABB generic research and development activities, the specific needs associated with steam cooled turbine vane will need to be validated within the program.

ABB has, since the early seventies, used a conventionally cast nickel-base super-alloy, IN 738, in the hot sections of the gas turbine. IN 617, a sheet alloy, is the preferred alloy for combustor liners.

In developing systems for the next family of power generation turbines, the increased gas turbine entry temperatures necessary for improved cycle efficiency, coupled with

the need to maintain or reduce environmentally degrading emissions, results in a lower availability of cooling air for the turbine components. Thus, improved temperature capability components are required. These can be realized by a combination of improved material capability and high cooling-efficiency design. From the materials technology perspective, these changes require an integrated approach for improved materials and manufacturing processing. The high efficiency cooling designs place a premium on manufacturability. For blading, Figure 12 illustrates the increasing complexity relative to castability of aero-engine turbine blade cross sections.

As Blade Geometry Increases in Complexity;

- Improved Core Technology Needed for Dimensional Stability
- Casting Process - Design Interaction Optimization Required.

Figure 12 Improved Cooling Efficiency
Requires Improved Casting Technology

Through a combination of new materials and advanced cooling technologies, it is planned to raise the turbine inlet temperature by 100°C. The contribution from advanced materials alone is estimated to be 50°C. The application of steam cooling to the blades and vanes of the turbine will give a further increase of TIT of 150°C, bringing the total TIT increase to 250°C. While ceramic materials offer some further improvements in materials temperature capability, we feel that their incorporation in this program would present unnecessary risks. All planning efforts are therefore focused on the use of advanced nickel-base superalloys. The requirements for superalloys differ greatly for aeroengine applications and for applications in land-based gas turbines. The main difference in land-based gas turbines is the different fuel, which in the case of oil, partially also with gas, is more corrosive than jet engine fuel; furthermore, the expected life of blades and vanes in industrial turbines is 50,000 hrs. compared with a shorter design life of aeroengine components. This has important consequences for the development of superalloys and has led to diverging families of alloys. In order to improve the corrosion resistance, the chromium content has to be raised from about 9% to 13-15%. Increased amounts of chromium reduce the capacity of the alloy to accommodate those alloying elements which strengthen the nickel-chromium matrix by precipitation hardening, and increases the propensity to form brittle phases.

Traditionally, the land based power generation gas turbines have utilized conventionally cast blading alloys with oxidation/corrosion protection coating. ABB has traditionally used high chromium containing alloys such as IN738LC (16% Cr as compared with 6 - 9% in typical aero-engine alloys), and chromia forming vacuum plasma sprayed coating such as the ABB proprietary SV20. These systems, combined with relatively conservative cooling efficiency designs have performed well relative to competing systems. Figure 13 illustrates the family of corrosion coatings available, and the surface temperature limits for 24,000 hours life.

Figure 13 Comparison of Blading Coating Temperature Capabilities

As firing temperatures have increased, an increase in blade cooling efficiency has been necessary. Highly cooled blades tend to suffer from material damage accumulation during temperature transients. Thus the trend has been away from blade life limitation due to creep damage accumulation, towards limitations because of thermo-mechanical fatigue damage. (Also known as LCF damage.)

ABB has invested considerable funds to formulate advanced computer codes to predict the generation of brittle phases and to maximize the volume content of precipitates. Alloy compositions have been formulated which will give a significant increase in temperature capability.

Besides using new chemical compositions, the result of alloy development, the high temperature mechanical properties of superalloys can further be enhanced via suitable manipulation of the orientation and size of the grains in a casting. At metal temperatures above 760°C (1400°F), the grain boundary becomes the weak link under conditions of static stresses. Casting techniques have been developed to place the grain boundary either parallel to the loading direction (DS or Directional Solidification) or to eliminate the grain boundary altogether (SC or Single Crystal solidification). The quality of the cast components depends critically on the proper choice of micro-alloying elements, responsible for castability and the prevention of recrystallization in single crystals.

The trend towards DS and single crystal turbine blading is being followed by all major land based power generation gas turbine suppliers. At ABB, demonstration castings over 600 mm (24 inch) in length have been produced. However, in order to permit large DS and SC blading to be cost effective, the casting scrap rates must be reduced. Typical scrap rates for large (>250 mm, 10 inch) PC castings are 5 - 15%, for aero-engine DS and SC blades castings up to 150 mm (6 inch) scrap rates in the range of 20-30% are considered acceptable. ABB is working with casting vendors in order to make available high yield rates for its new family of cooled blading for utility sized components. These technologies will be made available to the ATS project.

ABB's own focused materials research program will lead to a successfully cast DS-blade from an advanced alloy giving a 35°C increase in temperature capability by 12/93; a single crystal blade from an advanced alloy giving a 50°C increase in temperature capability will be demonstrated by 12/94.

Without taking into account the concurrent improvements in blade cooling technology, these two advances by DS and SC technology will give increases of T.I.T. of 70 and 100°C, respectively. An important feature of our program involves the introduction of steam-cooling to blades.

5.1 DEVELOPMENT AND TESTING PROGRAM FOR STEAM COOLED COMPONENTS

The design of a steam cooled blade would follow normal design procedures employing knowledge gained from past cooling designs with care being taken that the change of the solubility of the steam does not lead to deposits in the cooling passages. The cooling of the trailing edge portion of the vane represents the most technically challenging part of the design due to the constrained geometrical space here which must house the cooling system.

The new cooling concept is to be verified by testing a scale model of the internal cooling system at the correct Reynolds number. The model scale, mass flow rate and gas density are chosen as necessary to give the most detailed local heat transfer and pressure loss information. Typically, heat transfer measurement techniques based on thermo-chromic liquid crystals are used with plexi-glass models and placed in pressure vessels, if needed, to achieve the proper density to simulate actual engine Reynolds and Mach numbers within the cooling passage. Calculations indicate that the same techniques can be used to simulate cooling systems designed for use with steam. The results of these tests combined with prior knowledge of the vanes external aerodynamics and heat transfer characteristics give the vanes cooling system efficiency and effectiveness. The effectiveness is expected to increase by approximately 0.15 due to the increased heat capacity of the steam without increasing the complexity of the cooling system technology from what is currently employed in air cooled systems.

Following the scale model verification and material tests, testing of steam cooled vane prototypes are planned in guide vane cascades and/or actual engine application in collaboration with a utility customer under real design conditions of ATS. The prototype tests will demonstrate the feasibility of using steam cooling confirming the cooling

efficiency and higher effectiveness predictions, vane mean metal temperature and expected life time.

Mechanically, integrity of the final component will also be checked and the criteria for bulging and cracking of the vane outer skin will be established. This can be done by merely pressurizing the inside of the vane and measuring its deformation rate.

The results of the design and testing of the steam cooled guide vane will be compiled and reported. The testing level of detail will be such that future designs of steam cooled systems based upon the concepts developed here can be made with a high level of confidence. Early tests can be initiated in 1993: 1) Systems Design, 6/93 2) Cycle Optimization, 9/93 3) Design of Cooling System, 12/93 4) Single Blade Test, 6/94.

A further development need is to conduct a 16,000 hour testing of various superalloys, including single crystal materials exposed to the cooling steam environment at two temperatures up to 2000°F (at ambient pressures). Specimens will be examined at several times during the test exposure visually and metallographically. Testing can be done in existing facilities at ABB. The data will indicate the cycle behavior of these materials under a high temperature steam environment and can be utilized for materials selection for the steam cooled parts.

6. OPERATING AND CAPITAL COST

We used as a reference 1991 power plant, a green-field combined cycle power plant as a basis for Operating and Capital costs. The plant with 239 MW net output at 59°F (15°C) has a net heat rate of 7070 BTU/kW/hr LHV (cycle efficiency of 48.2%). So as not to be site specific, we excluded land acquisition, legal fees, taxes, etc. and used an EPC Contract price of \$598/kW*.

<u>Power Production Costs</u>	<u>1991 CC</u>	<u>Power Production Costs</u>	<u>ATS CC</u>
95% CF \$/kwh	.03087	95% CF \$/kwh	.02671
85% CF \$/kwh	.03208	85% CF \$/kwh	.02792

The 10% reduction in C.O.E. can be achieved over a 1991 reference plant and support an increased capital cost of 15% at an 85% capacity factor.

- * Basis 80% Debt
 - 8.25% Interest
 - 11.9 Mio \$ Annual Payment
 - 7.4 Mio \$ O&M
 - 3.0 \$/MMBTU Fuel Cost

It can be concluded that even with increased \$/kW plant cost, the ATS technology is viable. However, as the proposed plant would consist of only one GT HRSG and ST with a more compact footprint, some savings in capital cost could be realized. (Figure 14)

LEGEND

- 1 GAS TURBINE BUILDING
- 2 HEAT RECOVERY STEAM GENERATOR
- 3 ELECTRICAL MODULES GAS TURBINE
- 4 TRANSFORMERS - GAS TURBINE
- 5 STEAM TURBINE BUILDING
- 7 ELECTRICAL BUILDING
- 8 TRANSFORMER - STEAM TURBINE
- 9 HV SWITCHYARD
- 10 WATER TREATMENT PLANT
- 11 CHEMICAL STORAGE TANKS & UNLOADING
- 12 DEM WATER TANK
- 13 COOLING TOWER & COOLING WATER PUMP STATION
- 14 WORKSHOP
- 15 FUEL GAS METERING/REDUCING STATION
- 16 RAW WATER STORAGE TANK (OPTION)

Figure 14 2 Unit 1991 Vintage (240MW Power Plant)
Single Unit ATS (280 MW Power Plant)

7. RELIABILITY, AVAILABILITY, MAINTAINABILITY (RAM)

GT and CC design evaluation and practice is driven by industry demand for increased output and improved operating efficiencies. Generating unit RAM is a key cost/benefit/risk element which dominates the vast majority of requests for proposal for new CC capacity.

ABB is in the process of implementing RAM growth programs and of defining a rigorous "Design for Reliability" approach. High RAM features lead to the ability to reduce overall generation system reserve margin requirements; i.e., decreased needs for future capacity, which can yield large capital and economic savings. Combined cycle plants have average forced outage factors in the two to five percent range. The key reliability elements of a CC plant are the gas turbine, the steam turbine generator, the heat recovery steam generator (HRSG) and the balance of plant.

The gas turbine remains for most CC layouts the most challenging component impeding RAM features. The heat recovery steam generator (HRSG) is much more reliable than a conventional fired boiler, since the HRSG is unfired and utilizes lower temperatures and pressures. The balance of plant (BOP) is also less involved than a conventional steam plant because of the less complex feedwater heating cycles required.

We evaluated reliability/availability data of new generation machines introduced such as the GT8 50 MW (New Transonic Compressor New Turbine, high T.I.T. & new controls) and the GT13E 147 MW (implementing higher efficiency components while increasing flow to increase 98 MW to 147 MW including T.I.T. increase). This data, especially that of a new machine such as the GT8 (1984) which showed certain deficiencies two years after first commissioning, still demonstrated high reliability and availability. Quick turnaround time and easy maintenance access for component change out is essential for improved RAM.

We specifically considered a complete combined cycle with a single unit operating for 30,000 hrs. at Hazelton, PA and found that with preventative maintenance program systems, reliability of 95% can be achieved. The key to BOP and Controls Reliability is preventative maintenance.

The RAM program must ensure that the design meets critical requirements, such as:

- starting reliability and availability factor (time performance measure)
- capacity factor (energy performance measure)
- equivalent operating availability (time/energy performance measure)
- a minimum of unit shutdowns during operating demand periods
- ease of maintenance
- availability of steam for GT blade cooling purposes

The following summary outlines a procedure which assures that the necessary requirements are introduced from the very beginning.

Issues.

1. An advanced turbine system is to be designed which meets RAM requirements.
2. Define design parameter for all systems which have to be checked during the design process of all systems.
3. Define plant operation which is to be taken as the basis for all design checks referring to RAM.

Solution.

1. The following Main Documents will be taken for all RAM Analysis checks:
 - Plant P&ID to optimize the system design
 - Plant Single Line Diagram to optimize the electrical system design
 - Plant Layout to carefully check maintainability
 - Plant Operational Concept to optimize all operational modes
 - Basic design specifications of all systems
 - Investigation of technology improvements which exceed the current envelope of experience.
2. The checks will be based on an Experience Basis.

The checks will be concentrated on the system designs and all component performances.
3. In addition, a design verification will be introduced which is to assure that all designs which exceed the envelope of experience are carefully tested.

It is, therefore, necessary in the next phase of ATS to introduce a procedure to compare new features with actual experience, in parallel with the development of the design. These steps will avoid repetitive deficiencies and will minimize the necessary steps to increase RAM experience from the first unit in operation to the Nth unit.

8. COMMERCIALIZATION - NATURAL GAS-FIRED REFERENCE SYSTEM

The ABB team is convinced that the advanced gas turbine system (ATS) technology power plant fits a variety of market requirements. The team believes that a substantial market exists and will further develop for installation rated between 100 and 250 MW modularized construction that is easily transportable and suitable for fast installation. However, one of the major issues for any new technology is customer acceptance. From the customer point of view, the question is whether the potential advantages of new technology offset the risks involved; what cost, reliability, maintainability, and size criteria must be met for an electric utility to buy an advanced gas turbine system? The Task 1 (Phase I) study is a first important step in that direction. The results of this study and subsequent work should greatly help in answering these questions. Further R&D work, however, is required and demonstration plants and first commercial deployment plants would have to be built before a satisfactory answer becomes available.

Demonstration Plant

The primary technology issue for commercialization is to achieve successful performance demonstration of the selected system. The logical step is to build a demonstration plant. To reduce cost, it is recommended to build a retrofit demonstration plant in the size range of current engine size. These are several power stations which have small generating units and are to some extent inactive. The units which have been shut down for various reasons would still have the available steam turbine generators and balance of plants support systems suitable for continued operation. Furthermore, an interest in reactivating these units exists, if they can be made to operate economically and reliably, which is one of the objectives of this program. It must be recognized that the demonstration plant, although very attractive to the host utility, involves risks, and these should be substantially sponsored by DOE and possibly EPRI and other institutions.

Product Introduction

ABB would establish a Product Introduction Organization, similarly as done today, driven by a Product Manager with commercial experience working directly with the Development Manager. The Product Manager assumes responsibility for first unit logistics, commercial success working within and parallel to the development team, with autonomy and resources adequate to do the job. The success of this structure is evidenced by recent introduction on three new products for power generation in 60 Hz and 50 Hz markets. Product Introduction or Commercialization breaks down into three overlapping schedules: Development Program, Market Introduction and Project Execution. The schedules illustrated are typical and in this sub-task ABB will develop a commercialization plan using the illustrated tools. (See charts 1 through 4).

- o Organization evolves over introduction cycle (eg. Product Manager in development team during Phase A)

Chart 1 Recommended Product Introduction Organization

Q = Quarter

Chart 2 Product Introduction Schedule

Q = Quarter

Chart 3 Product Introduction Schedule

Q = Quarter

Chart 4 Product Introduction Schedule

First Commercial Plant

The major objective of the first commercial plant is to demonstrate reliability, economic competitiveness, and to evaluate performance of the commercial marketable unit. The design, fabrication, start-up, and operating schedule has to be judiciously drawn up to ensure proper timing of a market breakthrough. It will require monitoring the market needs and demands on a regional basis and throughout North America and, for that matter, on a worldwide basis. This will be supported by further market studies.

Preliminary cycle studies indicate the objective of high efficiency Reference Cycle is achievable. Furthermore, many of the components utilized in the cycle evaluations are state-of-the-art. This feasibility assessment would indicate that the commercial deployment of high efficiency systems could be accelerated to late 1990s. The team's objective is to be a participant in the commercialization of a selected Reference Cycle configuration of GT Combined Cycle with CCSC.

Lower electricity costs are in the economic interest of the USA and the manufacturing industry. With substantial investment in 50 facilities, as well as the growing importance of ABB's Turbine Manufacturing Division in Richmond, commercialization of the ATS program will be a primary factor.

Business Factors In Support Of Commercialization

- Evolutionary technologies in Company's Strategic Plan, Phase I selection
- Availability of engineering capabilities to support the Plan
- Market interests and needs
- Marketing expertise
- Manufacturing facilities to support the plan
- Financing alternatives to implement the Plan
- Host utilities - consortia and joint ventures

Market Development

It is considered very important to acquaint the utilities with the advanced power plant concepts with emphasis on their economics and advantages to develop a market for this technology. It is recommended that EPRI, and GRI, with DOE's leadership, take various steps to promote the technology with potential clients. Active steps under ABB's guidance will be initiated, which would provide more definitive data on performance optimization and system selection. This effort should be focused especially toward those utilities who would be making power plant additions and would be the likely candidates for the proposed advanced technology gas turbines.

Keeping utilities informed of the progress made by the proposed technology throughout the various phases of this program is a necessity. The utility response would finally decide the market potential, expected market share, and commercial plant size; only then can the return on investment be evaluated. The on-going market development activities, which should be started at or during Phase 2 by the team members, will end only after the technology becomes fully commercial.

Chart 5 Peak Demand and Capacity

Commercialization Timing

The developed product introduction plan will be implemented continuously with the work scope of the proposed phases.

Phase I - 1992	System Scoping and Feasibility Studies
Phase II - 1993/1994	System Definition and Component Development
Phase III - 1994/1997	Testing of large-scale components and systems
Phase IV - 1998/2002	System demonstration

The timing and support effort required has Senior Management's commitment to commercialization of evolutionary and revolutionary gas turbine power generation systems.

Company Experience/Facilities Relative To Commercialization

Advanced Utility GT CC Developer Experience

Since the first industrial GT went commercial in 1939 (BBC), ABB focused on improved GT cycles. The first CC went into service in 1956, and the first CC in the world to be officially tested at 52% went into service in 1989. ABB has taken the next step for a

commercial CC plant with 54% efficiency to be placed into service in 1994/95. In addition to component and steam water cycle development and improvement, ABB embarked on a combustor development program to reduce NOx emissions in 1986. The unique dry low NOx, lean-premix EV-burner concept was developed and commercialized in 1991. In addition, PFBC has been developed and demonstrated and air-blown gasification (IGCC) by ABB/CE has been developed to the demonstration phase.

Materials and Manufacturing Experience

ABB today participates in a global economy and manufactures in several countries. The Turbine Manufacturing Division in Richmond, Virginia, which already plays a key role in gas turbine shipments to utility customers' current and future planned operational needs as far forward as 1996, will be expanded substantially to accommodate the expanding 60 Hz market. Local sourcing has become a prime focus to encourage foundries and forge masters to redirect their efforts. This redirection is already occurring as a result of demilitarization and changes in the auto industry.

Research Facilities and Equipment

ABB TPD has many resources at its disposal for the development of advanced stationary gas turbine components. These resources have been used successfully to develop a new pre-mix low NOx burner capable of NOx emissions of less than 10 ppm by employing vortex breakdown principles to stabilize the flame front. The development of this combustion technology has earned ABB the ASME International Gas Turbine Institute's 1990 Award for best Application paper. The success of this burner has led to the development of the world's first annular combustor for large stationary gas turbines (ABB's GT13E class of turbines rated at 150 MW).

R&D resources are also routinely used to investigate basic aerodynamics and heat transfer mechanisms as they apply to the gas turbine environment. This has led to the development at ABB of thermo-chromic liquid crystal heat transfer measurement technique which is currently being used to investigate heat transfer mechanisms on fundamental and actual ABB turbine blade geometries. Experimental investigations are being conducted currently to investigate the fundamental mechanisms and effects of pin-fins, ribs and film cooling on local and average heat transfer rates.

To study external aerodynamics and heat transfer, cascades of guide vanes or blades can be tested at engine Reynolds and Mach numbers. To supplement the experimental work, a variety of computational fluid dynamic programs are available ranging in complexity from inviscid Euler flows and boundary layers codes to full three-dimensional time averaged Navier-Stokes simulations. These codes are typically employed to analyze new designs and investigate problem areas resulting from scheduled inspection of installed turbines.

The Turbomachinery Laboratory at ABB has several Turbine Test Facilities. These range from single stage to full five stage units. Detailed aerodynamic measurements can be made using multi-hole probes, pressure tappings on stator and rotor parts and Laser Velocimetry. The five state turbine test facility has a series of clutches so that

the torque output from each turbine stage can be measured individually in order to establish each stage efficiency.

A high pressure, high temperature burner facility is also available which can be easily modified to accept a cascade of five scale (3:1) vanes or blades for endurance testing of hot section components.

ABB R&D Expenses

ABB R&D expenses are 8.1% of group revenues or \$2.3 billion of which 5% is allocated to basic research and research in scientific key areas, and 95% in business responsible units for development of pacemaking core technologies and product development. Six research centers in Europe specialize in Combustion & Fluid Dynamics, High Temperature Materials, Insulation Systems, Current Interruption and Limiting, Rotating Machines, Super-conducting applications, ASCII, Gaseous Air Pollution Control, Main Machine Communication Control, Software Engineering, Computational Methods.

In the USA Power Plant Laboratories, Windsor, Connecticut is strategically oriented to work with the ABB Power Plant Businesses. In 1992 R&D expenses totaled \$24 MUSD, with 150 employees. Major research areas: Combustion and Fluid Dynamics, Process and Cycle Analysis, HT Materials and Water Chemistry, and Electronics and Electrical Systems. Main projects: Low NOx burner technology for boilers, advanced boiler design, HRSG Cold Flow Modeling, Computational Modeling, IGCC, Black Liquor Gasification, Structural Mechanics, Instrumentation and Control Equipment for Power Plant Control, and specialized sensors relating to boilers and power plants.

The focus is for more efficient and clearer power generation and distribution; the company excels at adapting its products and technologies coming from R&D facilities to meet clients' needs, utilizing USA and international experience for each of its customers: electricity-generating utilities, independent power producers and industrial plants, manufacturing industries and municipalities.

9. POTENTIAL MARKET OPPORTUNITIES

Current View of Market Opportunities

The world market, as presently perceived for gas turbines, suggests a market of 17 GW+ for GTs larger than 30 MW by 1997 with a decided shift towards combined cycle $\pm$ 20 GW. The 50 and 60 Hz markets are evenly split 13 & 14 GW, respectively, dominated with larger units to 170 MW and larger than 170 MW for 50 Hz. The charts 6 and 6A illustrate this clearly. The 60 Hz market extends to the export sector as well.

The world market for gas turbines over 10 MW in size has increased rapidly and has been at record levels since 1989 when megawatt awards reached 23 GW from a 13 GW level. The year 1990 saw order awards of 28-29 GWs and 1991 saw over 25 GW. The requirements for "instant" power plants with high efficiencies encouraged combined cycle power plants where net efficiencies of over 52% (LHV) are obtained in power plants constructed in 1989. Current awards are for combined cycle power plants in excess of 53% using advanced large gas turbines in the 50 Hz market.

Availability of natural gas, LNG, etc. has spurred on development of "clean" power plants, where coal has been a dominant fuel, or heavy oil, because of the unavailability of natural gas. Privatization in the United Kingdom, Eastern Europe, etc. has opened new opportunities.

It can be concluded that development of a new generation system on a regional basis could be of significant benefit not only to the 60 Hz market which extends beyond North America, but also in the 50 Hz market where turbomachinery adapts well to scaling operating at 50 Hz speeds or in smaller units using reduction gears.

SC/CC

50/60 Hz

Chart 6 Market Opportunities

POWER RANGE 60 Hz

POWER RANGE 50 Hz

Chart 6A Market Opportunities

U.S. Market Outlook

In this study we considered awards by technology to identify the scope and capacity for application of ATS gas-fired systems. Reserve margins and other key drivers were examined with a substantial existing database of 130 U.S. utilities, 75 independent power producers. With access to the ABB group marketing resources, opportunities are clearly viable for the ATS reference cycle starting in the late 90s when current technology systems could be displaced. Recent studies of new capacity in the U.S. are reported by the DOE to be 250 GW by the year 2000 driven by the Clean Air Act of 1990 and rehabilitation of older plants which will require performance improvement.

ABB sees an average annual rate of 2.3% through the year 2000 and a decline to 2.1% through 2010, which is impacted by conservation, and demand side management programs driven by rising electricity prices. ABB also takes note of capacity that may be committed as far out as the year 2000. Furthermore, looking at a utility forecast of 2% per annum average versus a Bechtel study ($\approx 3\%$ /year average), this difference could amount to 60 GW by the year 2000. It illustrates the significant impact small changes in growth rates have on the need for new capacity.

Key Drivers & Assumptions

Due to differences in electricity demand growth, our projection of needed capacity is greater than the utilities' projections because we believe utilities are underestimating electricity growth for the 1990s. The utilities' projections are aggregated each year by the North American Electricity Reliability Council (NERC). Representing independent projects of each utility, the aggregate projection has been consistently lower than the actual load growth over the past six years, even for a one-year forward projection. The close relationship between GNP and electricity has been modeled extensively. In addition, our projection assures electricity prices will not rise in real terms until the mid-1990s. Rising prices in the mid-1990s will set the stage for slower electricity growth in the late 1990s. The range in electricity growth forecasts is partially due to differences in outlook on the U.S. economy in the long term. These differences are also due to economists inability to agree about electricity prices and how modest changes in price impact electricity growth.

Declining reserve margins and electricity growth drive the demand for new capacity. ABB forecasts electricity growth at an average annual rate of 2.3% through 2000. The annual growth rate is projected at 2.4% through 1998 and decline to 2.1% through 2020 due to the impact of conservation and demand side management programs driven by rising electricity prices.

Chart 7 **U.S. Electrical Generation Growth**

Other key drivers include reserve margins criteria, retirements, imports, and demand side management. The projection calculates a new annual retirement (retirements minus uprates to existing units) of about 2700 MW through 2000. Most of these retirements are projected to occur in the year 2000 as a result of compliance with Phase II of the Clean Air Act. In the late 1980s, utilities were reporting their future retirements at an average rate of 100 MWs to 1500 MWs per year. Strategically, utilities no longer have interest in retiring a unit unless the unit requires too much capital to maintain it in operable status.

Reserve margins are projected in the 15 to 20% range depending on the region. On a national average basis, reserve margins are forecasted to decline to 18.5 to 19.0% by the year 2000 (a reserve margin of 19% is equivalent to a capacity margin of 16%). The projection also includes 10,000 MW of a load management and 7800 MW of imports from Canada or equivalent firm capacity by the year 2000.

Forecast of Awards

The awards forecast viewed, translates the in-service projection into awards by year, by technology and by customer. The award year is not necessarily the booking year of the contract. These awards for power plant MWs lead by several years, for most GT projects approximately 3 years; large CC or IGCC, 4-5 years.

It becomes necessary to communicate technological advances at an early date so that consideration can be given to performance improvement by Power Generating companies for their projected capacity and system requirements.

Recognizing the need for technology advances, the California Energy Commission and PG&E have considered efficiency improvement as a key priority and identified 7000 MWs of replacement or repowering of aging fossil-fuel-fired plants, and initiated advanced turbine program studies to identify early solutions.

ABB's Marketing Expertise

ABB is a global organization in marketing power plant systems, ranging from nuclear, coal, gaseous fuels, hydro, and refuse-derived fuels (RDF). Marketing in the power plant sector is done on a regional basis. The U.S. is one region, including North and South America. Within the U.S., the power plant segment is divided into five regions, which in turn, are supported by the different business units, such as the turbine power division and the appropriate technology centers.

Coordinating worldwide activities is done from Baden, Switzerland. This provides a constant overview of power generation needs and the changes demanded by the marketplace in terms of environmental controls, efficiency, reliability and fuel availability.

The need for improved generation systems, incorporating advanced technologies under the worldwide scenario of application, operation, maintenance, and fiscal viability is therefore constantly screened and reviewed to ensure that new products are brought to the market in a timely and cost effective manner.

ABB U.S.A.

The ABB, Inc. revenues for 1991 were \$5.5 billion (19% of ABB groups of companies) supported by 29,000 employees (14% of ABB group), and more than 50 U.S. manufacturing facilities. Power Plants 36%, Power Transmission 20%, Environmental Control 10%, Power Distribution 2%.

Figure 15 ABB U.S. and International Revenues

The turbine manufacturing facility in Richmond, Virginia will be substantially expanded in 1993 as a worldwide facility for 60Hz domestic business and export. In 1991 27% of U.S. revenues came from the international sector.

10. COST OVERVIEW

Program costs were developed to cover the four basic phases.

Phase 1	Program Definition	- Final Report
Phase 2	Design Process	- Proposal in Evaluation
Phase 3	Procurement of 1st CC Plant	- Estimated Cost
Phase 4	System Demonstration	- Estimated Cost

The costs and cost share are indicated on Chart 8.

		Contr.	DOE		
		Cost-	Cost	TOTAL	
#	Description:	share	share	costs	
		\$ k	\$ k	\$ k	%
1.00	Program Definition	12	95	107	Inv.
1.01	Market Requirements				
1.02	Definition of " TECHNOLOGY BASE".				
	Phase 1:Subtotal	12	95	107	0%
2.00	Design Process				
2.01	Cycle Concept Determination	589	2,262	2,831	RFQ
2.02	Special Tests	201	1,554	1,754	RFQ
2.03	System Design	4,231	41,185	45,415	Est.
2.04	Critical Component Definition			Incl.	Est.
	Phase 2:Subtotal	5,000	45,000	50,000	19%
3.00	Procurement of the 1 st CC Plant 250 MW	136,000	34,000	170,000	Est.
3.01	All Software				Est.
3.02	All Hardware				Est.
	Phase 3:Subtotal	136,000	34,000	170,000	64%
4.00	System Demonstration				Est.
4.01	Installation and Commissioning	12,000	3,000	15,000	Est.
4.02	Project Demonstration	1,500	13,500	15,000	Est.
	3 years: approx. \$ 2.5 M/year & \$7.5M for Equipm.				
4.03	System Modifications based on Testresults	1,500	13,500	15,000	Est.
	Phase 4:Subtotal	15,000	30,000	45,000	17%
	TOTAL	156,012	109,095	265,107	100%
		59%	41%	100%	

Chart 8 DOE ATS - Program
Cost Overview

11. CONVERSION TO COAL-FUELED REFERENCE CASE

ABB has made many conceptual designs for coal-fueled systems incorporating today's gas turbines. There are several advanced coal fueled systems being developed which may have advantages such as better efficiency and lower emissions. These systems include:

Coal Gasification Combined Cycle - both integrated with the power plant (called IGCC, Integrated Gasification Combined Cycle) and non-integrated with gasifier and power plant at separate locations.

Pressurized Fluidized Bed Combustion - both the current generation with modest turbine firing temperatures of about 1600°F (871°C) and the advanced concepts with higher firing temperatures.

Externally Fired Cycles - in various configurations, with high temperature heat exchanges.

Integrated Gasification Humid Air Turbine - where the steam cycle is eliminated and the gas turbine provides all the power.

Even before this current study, ABB has investigated most of these concepts and is very active in IGCC and PFBC.

For the purpose of this study, ABB has identified IGCC as the coal-fueled system to which we would like to adapt the advanced gas turbine. Some of the factors in this selection include:

The combined cycle is a proven cycle with high efficiency. As we chose the combined cycle for our natural gas-fired reference system, we believe the same advantages apply to the coal-fueled system.

There are many parties developing gasification and IGCC systems and there are many configurations being considered for gasification systems: gasification for chemical feedstock production, IGCC, cogeneration applications, IGCC with off-peak chemical production, etc. Thus it appears that gasification and IGCC have great potential to be commercialized in the near future.

Given that IGCC is the selected coal-fueled system, there are still many variations which impact the gas turbine design. One issue is in the source of the oxygen for gasification. In most oxygen-blown gasification systems, an independent air separation unit (ASU) supplies oxygen to the gasifier. No air is extracted from the gas turbine compressor for the gasification process, and the fuel to the gas turbine is all extra mass. Since the coal gas has a lower energy density than natural gas, there is more extra mass flow, which has implications for balancing the compressor and expander.

Most air-blown IGCC concepts and oxygen-blown IGCC with an integrated ASU extract the air for gasification from the gas turbine compressor. This requires a design change for the extraction, which in turn means less extra mass flows through the turbine expander.

The following three sections which discuss the gas turbine design impacts consider all of these factors. For performance and emission estimates, we have used an oxygen-blown gasification system with no air extraction for the purpose of the illustrative calculations.

Implications for Gas Turbine Design

Integration of the advanced gas turbine into an IGCC system will require some changes in the gas turbine design:

- A. Extraction of Compressor Air - Some IGCC configurations require extraction of air from the compressor for the gasifier. As the turbine firing temperatures rise, however, more of the compressor air is required for cooling, leaving less available for extraction. The steam cooling provides a significant advantage in this regard for oxygen-blown gasification as extraction is not needed, as the GT will have sufficient margins.
- B. Environmental Factors - NO_x , CO, and unburned hydrocarbon (UHC) emission will be influenced by the fuel fired in the gas turbine combustor. Modifications to the combustion system may be required. Other pollutant such as SO_2 and some air oxides will be less dependent on the turbine combustion system, but depend more on the gasification process.
- C. Materials Implications of Fuel Quality - In an IGCC system, products of coal combustion pass through the turbine section. This gas will contain some level of sulfur, alkalis, metals, and particulate which can harm the turbine materials and degrade the performance. Possible impacts include selection of materials, allowable temperatures, and tolerances.
- D. Compressor/Turbine Balancing - In today's natural gas combined cycles, the added fuel is about 2% (wt) of the compressor air flow. With the higher firing temperature of the advanced turbine system, it could be about 2.5%. In an IGCC system, a higher percentage of added mass will flow through the turbine, which has implications for balancing the compressor and turbine sections.

Note that some of these factors can be addressed in the gasification system as well as in the gas turbine.

An IGCC system can be designed with air extraction from the compressor or with a separate source of air.

The gas turbine materials can be protected by more stringent cleanup of particulate and alkali if necessary from gasifiers.

Ammonia removal from fuel gas has been considered to reduce the levels of NO_x from the turbine combustor.

Performance of the IGCC System

The steam bottoming cycle used in the coal-fueled combined cycle system for these calculations is similar to that in the natural-gas-fired reference system - three pressure levels with reheat and steam cooling of the gas turbine. There are two differences between the two steam cycles:

In natural gas fired combined cycles, the exhaust gas has a very low sulfur content so the stack temperature can be very low without concern for acid dewpoint. To achieve a low stack temperature, the feedwater coming into the economizers should be cool. Feedwater heaters raise the temperature of this feedwater, so in the natural gas reference case we had no feedwater heater other than the deaerator. The feedwater enters the HRSG at the deaerator temperature of about 55°C (130°F) and cools the stack temperature to about 80°C (175°F). In the coal fueled case, the exhaust gas contains more sulfur, so the stack gas cannot be cooled to the same extent. With one additional feedwater heater, the feedwater enters the HRSG at about 100°C (212°F) and cools the stack gas to about 120°C (250°F). (Figure 16)

Figure 16 Heat Recovery Diagram - IGCC

In the IGCC system, the gasification process gives up heat which is used in the steam cycle. In the present calculation, 16% of the coal's lower heating value is used to generate high pressure superheated steam. Feedwater is taken from the HRSG after the second high pressure economizer and taken to the gasifier island. The superheated steam is mixed with that from the HRSG just before the high pressure turbine. This affects the distribution of heat duties in the HRSG somewhat, since the first two economizers in the HRSG handle the full high pressure flow but the third economizer, evaporator, and superheater in the HRSG handle just a portion of the full flow. (Figure 17)

Figure 17 **ATS Cycle with Gasifier Island**

The oxygen-blown gasifier in the calculation is assumed to have a cold-gas efficiency of 80.3%, i.e. 80.3% of the coal's LHV shows up as fuel gas LHV. In addition, some sensible energy is in the fuel gas. The estimated overall efficiency of the cycle is 52.17% (LHV basis). An air-blown gasifier would be expected to have a performance improvement because of the auxiliary power requirement of the ASU in O_2 gasifiers. This will require further investigation with developments taking place in Air Blown Systems.

In a recent development program, the low NO_x EV-burner (slightly modified version) successfully completed a series of tests with a simulated MBTU gas under real high pressure engine conditions. The EV-burner works in a pre-mix mode without flashback and NO_x emission levels measured lower to 25 vppm @ 15% O_2 .

GTs using this EV-burner concept can now use an independent ASU, Figure 18, which will be superior to all integrated ASU concepts with respect to electrical efficiency.

Figure 18 IGCC with Independent ASU

Gasification Process Description

The ABB CE gasification process uses an entrained-flow, slagging bottom gasifier. Figure 19 shows the main components of the gasifier island. Coal is pulverized to 70% through a 200 mesh screen and pressurized in a lock hopper system for feeding to the gasifier. The coal and the recycle char are fed to the gasifier. The coal and char are mixed with oxygen from an independent air separation unit, and the fuel-rich mixture is burned creating the high temperature necessary to gasify the coal and to melt the mineral matter in the coal. The slag flows through a slag tap at the bottom of the gasifier into a water-filled slag tank where it is quenched and transformed into an inert, glassy, granular material. This vitrified slag is non-leaching making it easy to dispose of in an environmentally-acceptable manner.

Figure 19 ABB C-E IGCC Flow Diagram

Gasification occurs along the height of the gasifier until the temperature falls to a point where the gasification kinetics become too slow. Once the gas temperature reaches this level, essentially no further gasification takes place and the gases subsequently are cooled with convective surface to a temperature low enough to enter the cleanup system. Thus, nearly all of the liberated energy from the coal that does not go into producing fuel gas is collected and recovered with steam generating surface either in the walls of the vessel or by conventional boiler convective surfaces in the backpass of the gasifier. This boiler style design provides for recovery of coal energy as either fuel gas or steam (for use in the steam turbine to generate electricity).

A mixture of unburned carbon and ash (called char) is carried out of the gasifier with the product gas stream. The char is collected and recycled back to the gasifier where it is completely consumed. Thus, there is no net production of char, which results in negligible carbon loss.

The product gas then enters a desulfurization system where it is cleaned of any sulfur compounds present in the fuel gas. The clean fuel gas is now available for use in the gas turbine combustor for the combined cycle application.

There are many factors that affect the quality of the product gas derived from IGCC or PFBC, such as the contamination of the gas, the heating value, the flammability, and the composition of the gas. In view of the potential contamination due to the carryover of the ash from upstream of the gas turbine and the potential existence of the corrosive substances (sulfur, alkalis, and metals in ash/gas), a near free-of-contamination particulate removal system and gas cleanup system is critical to the success of the conversion from the gas turbine to the coal-fueled gas turbine. Special concerns shall address the more stringent cleanup of particulate and corrosive substances proper material selections for the critical elements, heat tracing of fuel lines, proper gas pressure in design, adequate inlet air filtration system, and proper safety consideration for the high hydrogen contents, etc.

Gas Clean Up

Conventional cold (less than 350°F) cleanup systems are commercially available for the particulate removal, such as the cyclones, baghouse filters, electrostatic precipitators, venturi scrubbers. Warm (350°F to 750°F) cleanup system also shows successful application in cyclones and electrostatic precipitators. At temperature higher than 750°F, advanced ceramic filter concepts are progressing, such as cross flow, candle, and tubular configuration or the baghouse with ceramic bag. Also available for the high temperature cleanup system is the granular moving bed concepts. In design a ceramic filter system for a high temperature environment, special concerns shall address the filter material selection suitable for the resistance of corrosion due to the gas/particulate substances and cleaning induced thermal shock, pressure drop across the system, cleaning media and its related pressure, cleaning frequency, collection efficiency, and durability of the system life. Recent high temperature (up to 2300°F) demonstration in 3M's Nextel baghouse filter or the SiC ceramic candle used in waste-fuel burning environment shows promising future in hot-gas particulate cleanup.

Sulfur Removal

If the desulfurization system is able to operate at the low end of the warm temperature range (i.e., 350 to 400°F), a commercially available system can be used. That system consists of a fixed bed of activated carbon preceded by a fixed bed of cobalt molybdenum catalyst. The cobalt molybdenum catalyst is used to convert the COS in the gas to H₂S before it encounters the activated carbon sorbent. Higher operating temperatures in the warm region require the use of iron oxide as a sorbent. Iron oxide, which has a maximum operating temperature of 750°F, is being demonstrated by CRIEPI in fixed, moving, and fluidized bed reactors.

For hot gas cleanup systems, zinc ferrite and zinc titanate catalysts are used as sorbents. Research has indicated that the mechanical strength of zinc ferrite catalysts limit their operating temperature to around 1000°F. Zinc titanate catalysts are expected to be able to operate around 1200°F. Both zinc ferrite and zinc titanate catalysts are being demonstrated by DOE in moving and fluidized bed reactors. The moving bed

tests have shown that the durability of the high temperature solids handling valves are a critical development issue.

With regards to cost, iron oxide is the least expensive of the metal oxide catalysts. Zinc ferrite catalysts are considered moderately expensive catalysts and zinc titanate catalysts are considered expensive catalysts.

Nitrogen and Halogen Removal

In the cold cleanup systems, halogen and nitrogen compounds are removed in the venturi scrubber. Further denitrification can be accomplished by injecting nitrogen or steam in the coal gas. The dry cleanup systems in the warm and hot temperature range, however, are not capable of removing halogen and nitrogen compounds. Thus, for dehalogenation, Na and Ca based absorbents are injected into the coal gas upstream of the particulate removal devices. The salts that form can then be captured by a particulate removal device such as a candle filter. For denitrification, SCR must be used downstream of the gas turbine to reduce the level of NO_x.

Efficiency

The Netherlands Agency for Energy and the Environment (Novem) has conducted a study which compares the efficiencies of IGCC systems using cold, warm, and hot gas cleanup systems. Novem compared the gas cleanup systems for both a Texaco and Shell gasifier. Novem looked at two warm systems, one which operated around 480°F (250°C) and one which operated around 660°F (350°C). For the hot system, they chose an operating temperature around 1110°F (600°C). The cleanup systems used at each temperature were as follows:

480°F Warm System

- Particulate removal by wet scrubbing
- Desulfurization by activated carbon
- Dehalogenation by scrubbing
- Denitrification by scrubbing and nitrogen injection

660°F Warm System

- Particulate removal by cyclones and candle filters
- Desulfurization by iron oxide zeolite
- Dehalogenation by pneumatic injection of soda
- Denitrification by SCR

Hot System

- Particulate removal by moving granular bed filters followed by candle filters.
- Desulfurization by zinc titanate moving bed
- Dehalogenation by pneumatic injection of soda
- Denitrification by SCR

The efficiencies for the cases looked at by Novem were as follows:

<u>Cleanup System</u>	<u>Efficiency (%)</u>	
	<u>Shell</u>	<u>Texaco</u>
Cold (120°F) - Wet	43.60	42.75
Warm (480°F) - Wet	44.54	43.68
Warm (660°F) - Dry	46.36	45.14
Hot (1110°F) - Dry	46.40	45.46

Looking first at the 480°F warm system, it can be seen that there is a marginal improvement in efficiency over the cold system. With the Shell gasifier, the rise in efficiency is caused by an increase in the steam turbine power and a decrease in the auxiliary power for the desulfurization system. With the Texaco gasifier, the moisture in the coal gas does not condense and the gas turbine generates more power. The steam turbine power decreases, however, because more heat is needed to heat up the coal gas after desulfurization.

The results indicate little difference in efficiency between the 660°F warm system and the hot system. For the Shell gasifier, the increase in gas turbine power is almost completely canceled by a decrease in the steam turbine power. The presence of an expander in the Texaco system accounts for the small increase with the hot cleanup system.

Waste Products

Using a warm or hot cleanup system instead of a cold cleanup system will eliminate some waste products, but will also add others. Examples of the waste products which would be eliminated would be sour water from the venturi scrubber and solvent lost from the acid gas absorber. The new waste products could include the following:

- Halide salts
- Spent sorbent from the desulfurization reactor
- Spent catalyst from the SCR reactor

The toxicity of the sorbent should depend on the type of sorbent used. Warm systems should have an advantage over hot systems because the sorbents used in warm systems, activated carbon and iron oxide, should be considered less toxic than the zinc ferrite and zinc titanate sorbents used in the hot systems. Of course, if the sorbent supplier can reclaim the spent sorbent then the toxicity of the sorbent may not be an issue. Likewise, SCR catalysts, which typically are titanium oxide based, may present a disposal problem if the catalyst supplier cannot reclaim the catalyst.

Cost

Novem compared the cost of electricity using the 660°F warm cleanup system with the cost of electricity using the cold cleanup system. The results were as follows:

<u>Cleanup System</u>	<u>Cost of Electricity (ct/kWh)</u>	
	<u>Shell</u>	<u>Texaco</u>
Cold	8.11	8.27
Warm (660°F)	8.21	8.10

Novem's numbers indicate that the use of a high temperature cleanup system does not necessarily result in a lower cost of electricity. Novem reports that the cost of electricity for the high temperature system would be lower for both gasifiers if the SCR plant can be eliminated.

Complexity

The use of a dry warm or hot cleanup system should result in a plant easier to operate since there should be fewer links between the cleanup system and the combined cycle. There should be fewer links because the gas is cooled down less before desulfurization and then heated up less after desulfurization. In addition, moisture in the gas is not condensed out, so there is no need to saturate the gas before it enters the gas turbine.

Cleanup Conclusions

Warm and hot cleanup systems offer several advantages over cold cleanup systems: higher efficiency, simpler operation, and (potentially) lower cost. When comparing warm systems with hot systems, warm systems are preferable, at least in the short term. Warm systems are preferable because they can either use commercially available technology or, if they use advanced concepts, should require less development because of the lower operating temperatures. At the same time, the efficiency of the IGCC does not suffer significantly.

12. CONCLUSION

The ABB selection for the Advanced Turbine System (ATS) includes advanced developments especially in the hot gas path of the combustion turbine and new units such as the steam turbine and the HRSG. The increase in efficiency by more than 10% multiplicative compared to current designs will be based on:

- Turbine Inlet Temperature Increase
- New Cooling Techniques for Stationary and Rotating Parts
- New Materials

Present, projected component improvements that will be introduced with the above mentioned issues will yield CCSC turbine performance of 40%, which will drive the ATS selected gas-fired reference CC power plant to 61.87% LHV.

The decrease in emission levels requests a careful optimization of the cycle design, where cooling air consumption has to be minimized. All interfaces of the individual systems in the complete CC Plant need careful checks, especially to avoid unnecessary margins in the individual designs.

Coal conversion with O₂ blown gasifiers with cold efficiency of 80.3% will provide estimated overall performance of 52.17% LHV.

This study is an important step pointing out the feasibility of the ATS program with realistic goals set by DOE, which, however, will present challenges for Phase II time schedule of 18 months. With the approach outlined in this study and close cooperation with DOE, ATS program success can be achieved to deliver low emissions and low cost of electricity by the year 2002.

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