Application of the Centaur Industrial Gas Turbine to the Central Receiver Concept for Solar Electric Power

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ABSTRACT

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INTRODUCTION

One important method of converting solar energy to electric power is thermal energy conversion in conjunction with an industrial gas turbine-generator set, and studies by the Electric Power Research Institute (EPRI) have shown that the solar-fossil hybrid turbine configuration in conjunction with the solar central receiver concept possesses significant advantages for utility electric power generation.

The design, modification and testing of a small, commercially available gas turbine is needed to demonstrate the technical feasibility of operating from two sources of input energy and to confirm the operating parameters being used in the EPRI pilot plant design definition studies now underway with the two central receiver contractors, Boeing Engineering and Construction and Black & Veatch Consulting Engineers (1, 2).

Currently available industrial gas turbines are designed to accept energy from the specific, fossil-fueled combustion systems associated with the engine and the application of the gas turbine to the central receiver concept presents several unique problems. This paper covers a design study performed by Solar Turbines International (STI), an Operating Group of International Harvester Company, with the objectives of developing conceptual designs of the hardware and systems modifications required to operate a STI Centaur recuperative gas turbine-generator set in a hybrid solar-liquid fuel mode.

CENTAUR RECUPERATIVE GAS TURBINE

The STI Centaur recuperative open cycle gas turbine is an outgrowth of the simple-cycle version originally introduced in 1969 as an industrial machine featuring rugged construction, moderate firing temperatures and long-life sleeve bearing design. The simple-cycle Centaur, shown in Figure 1, consists of an 11-stage axial compressor, an annular...
combustor and a 3-stage axial turbine section. This engine is supplied in both single and split-shaft configurations for applications including generator sets (continuous and peaking), gas compression and mechanical drives. Dual fuel versions are available burning natural gas or distillate liquid fuels up to #2 Diesel. The continuous rating of a single-shaft generator set at ISO conditions on liquid fuel is 2775 kilowatts. Almost one thousand of these units are in operation around the world and have accumulated in excess of seven million operating hours.

For the recuperative version, a heat exchanger is utilized. This is of "plate-fin" construction in low alloy carbon steel. An engine schematic is shown in Figure 2 where the recuperator is stacked vertically above the engine. The addition of the recuperator involves replacing the annular combustor used in the simple-cycle engine with a single can combustor mounted vertically between the recuperator and the turbine inlet scroll.

Figure 2. Recuperative Centaur Gas Turbine

In contrast to the wide range of applications and fuel types in use on the simple-cycle machine, the recuperative Centaur gas turbine is currently in service only as a natural gas-fueled, split-shaft gas compressor set.

Thus a study aimed at the definition of a hybrid recuperative Centaur gas turbine-generator set necessarily uncovers several key technology voids arising from the unique application and, in addition, other potential problem areas resulting from a lack of relevant engine operating experience.

STUDY CONSTRAINTS

During the initial stages of the study, a framework of constraints and guidelines were imposed to more effectively direct the main thrusts of the program. These were as follows:

**Engine Matching**

The recuperative Centaur engine is currently matched to a design point turbine inlet gas temperature (TITG) of 1144 K (1600°F) for a 288 K (59°F) ambient inlet temperature. This upper temperature limit is imposed by the required service life of the turbine components and the mechanical integrity of other hot-end items such as the combustor and turbine inlet scroll. An increase in the engine TITG would both increase output power and decrease the specific heat rate which could be directly translated into a decrease in required heliostat field costs. Any increase in matching temperature, however, without a major costly engine redesign, would result in unpredictable reductions of hot-end component life and engine reliability. For the purposes of the study, therefore, no consideration was given to increasing the engine matching temperature or to any major redesign of the compressor or turbine components.

**Recuperator Design**

The recuperator currently supplied for the Centaur gas turbine is an "off-the-shelf" unit with a design life of 15 years and has provided excellent service in the field in terms of total pressure drop and leakage rates when care is taken to minimize thermal gradients in the unit during the start-up regime. For example, a typical cold start-to-idle speed on the recuperative Centaur can take as long as 45 minutes. Because of the rugged design and construction of the unit a moderate design point effectiveness of 78 percent is obtained for the existing volume. Any improvement in recuperator effectiveness could again be translated into a decrease in required heliostat field costs, however, the application of a higher effectiveness recuperator would require considerable expenditures in terms of mounting and ducting redesign and such an improved recuperator would certainly be considerably more costly than the production unit. For the purposes of the study no consideration was given to alternate recuperator design.

**SYSTEM DEFINITION - HYBRID RECUPERATIVE CENTAUR GENERATOR SET**

There exist various options as to the arrangement of the overall engine system configuration based around the recuperative Centaur. The selection of the preferred overall engine system configuration was made using the general guidelines previously mentioned and a study of the individual sub-system operating parameters imposed by the various options.

The two main technology voids are in the areas of combustion and engine control. The study was concentrated in these two areas with the understanding that other possible problem areas would probably be secondary in nature.

**Engine Performance**

The overall engine performance has an impact on the configuration selection depending upon the projected pilot plant load profile. Figure 3 shows the performance characteristics of both split-shaft and single-shaft recuperative generator sets operating on solar thermal input only at an ambient temperature of 311 K (100°F) and an altitude of 320 m (1050 ft). The inlet temperature corresponds to the
average daytime maximum at Gila Bend, Arizona, a potential site for the pilot plant. The altitude is local altitude above sea level plus a projected 76 m (250 ft) tower.

The compressor efficiencies and airflow, turbine efficiencies, recuperator effectiveness and internal pressure losses correspond to minimum performance specifications for the recuperative Centaur split-shaft engine. The solar receiver pressure loss is assumed equal to the current production combustion system loss. Flow losses to the seals, turbine disc cooling and recuperator leakage are also equivalent to the production recuperative Centaur. A further one half percent leakage is assumed in the solar receiver. Standard reduction gearbox and generator efficiencies are used.

Although the specific heat rates of the split-shaft engine are superior to those of the single-shaft unit at part loads, the maximum output is less due to the reduction in gas producer speed and air mass flow. A study of the projected pilot plant load profiles lead to a preference for the maximum output and hence the single-shaft unit.

Combustion System

The combustion system analysis was made after several further guidelines were established. These were as follows:

* The gaseous exhaust emissions of the combustor such as carbon monoxide and nitrogen oxides would not be regulated to any particular levels and thus would not be a design constraint.
* A system design goal would be to produce no visible exhaust smoke at any operating condition. To this end, JP-4 liquid fuel could be used rather than a heavier distillate such as #2 diesel.
* Maximum use was to be made of the production combustion hardware as a cost reduction technique.
* System reliability was to be a priority item although lifetime requirements could be reduced to 12,000 to 15,000 hours from STI's design standards of 30,000 hours minimum.

Production Combustor—Re recuperative Centaur. As one of the combustion system guidelines was to make maximum use of existing hardware, a brief description of the standard combustor for the recuperative Centaur is presented.

The combustor is shown in Figure 4. It is approximately 43 cm (17 in.) in diameter with an overall length of 1.1 m (43 in.). The sheet material is Hastelloy X and the construction is welded and high-temperature brazed. The design is based on the Vortex Air Blast (VAB) concept where the reaction zone airflow is admitted to the combustor through a radial inflow swirler. When the swirling flow enters the reaction zone the radial static pressure gradients establish a toroidal recirculation which anchors the combustion process. The natural gas fuel is admitted through the swirler centerbody as a number of low velocity jets. The combustor is film-cooled along its length by internal splash rings which direct a fraction of the incoming air along the inside of the liner insulating the liner from the hot reaction products. The high temperature gases leaving the reaction zone of the combustor are quenched to the required turbine inlet gas temperature by a further supply of recuperator delivery air admitted through a series of dilution slots around the downstream section of the liner. The design point pressure loss of the combustion system is 4.5 percent.

Figure 4. Recuperative Centaur Can Combustor

As was previously mentioned, the production combustor is qualified only for natural gas fuel. Extensive development has been carried out, however, on the VAB concept for use as low-emissions combustion systems using liquid fuels.

Ignition of the combustor is by a torch igniter which protrudes into the reaction zone. The torch igniter is a small separate combustor with its own air, fuel and electrical ignition system. When activated at the beginning of the engine start sequence, a jet of hot gas is emitted from the torch that in turn lights the main combustor fuel. The torch igniter is not operated continuously and is deactivated after engine start.

System Requirements. The use of a liquid-fueled combustor in a hybrid application presents unique problems as the range of performance requirements for
the system is considerably greater. Not only must the combustion system be capable of starting the engine and bringing it to rated speed, and operating at any load without heat input from the solar receiver, but it must operate over a wide range of air and fuel flows when the combustor is required to augment the solar thermal energy. When the combustor is required for augmentation it is desirable that ignition be achieved smoothly at the minimum fuel flow so as to avoid large step changes in turbine inlet gas temperature. Two main options exist for the position of the combustor in the overall system; in parallel with or in series with the solar receiver. These options are discussed in the following sections.

**Parallel Combustor.** A schematic of a parallel combustor arrangement is shown in Figure 5 with a modulating control valve upstream of both the combustor and the solar receiver. The valves are required so that during the engine start phase all of the engine air flow can be delivered through the combustor. At design point conditions the opposite situation is in force with maximum airflow passing through the receiver and the combustor inoperational. In this manner the combustor does not impose any parasitic pressure loss on the cycle when not in use. When the combustor is required for augmentation purposes the valves are scheduled to maintain the desired maximum output temperature from the receiver. An advantage of the parallel arrangement is that the control valves and combustor are exposed to the normal recuperator delivery pressure and temperature conditions and a combustor system resembling the standard production unit can be envisaged.

![Figure 5. Parallel Combustor Schematic](image)

The standard production combustor design would not be suitable for direct use, however, because it has minimum airflow and fuel flow requirements for light-off that would be excessive for the duty under study where minimum output steps are required at combustor ignition and shut-down. A fuel staging modification as depicted in Figure 6 would increase the combustor operating range where a small pilot swirler is fueled for low airflow conditions and the pilot and main swirlers are fueled at full airflow conditions. At low airflow the pressure drop across the combustor is low which is not beneficial to the combustion process in terms of combustion efficiency. The pressure loss can be increased at the low airflow conditions by means of variable geometry. A relatively simple system is to physically separate the reaction and dilution air admission ports with an external control valve. At low flows, this valve can be used to duct all of the available air to the reaction zone thus increasing the pressure drop for better air-fuel mixing and higher efficiency.

**Series Combustor.** A schematic of a series combustor arrangement is shown in Figure 7 with the combustor downstream of the solar receiver. It was assumed that it would not be desirable to have the combustor upstream of the receiver with the exhaust products of combustion possibly fouling the insides of the receiver tubes. The system shown in Figure 7 avoids the complexity of control valves but it does involve a parasitic pressure loss across the combustor when it is not operating. The use of control valves to isolate the combustor when in full solar input mode is shown in Figure 8 but here the combustor valves are exposed to the receiver outlet temperature of 1144 K (1600 F) at the engine design point.

![Figure 6. Fuel Staged VAB Combustor](image)

![Figure 7. Series Combustor Schematic - Full Flow Combustor](image)

![Figure 8. Series Combustor Schematic - Isolated Combustor](image)

It can be seen that the inlet temperatures that the combustor is exposed to are considerably higher than those normally encountered, i.e., up to the maximum turbine inlet gas temperature of 1144 K (1600 F). Such high levels of inlet temperature are generally conducive to good combustion performance in terms of lean limit, combustion efficiency and smoke but may produce wall temperature problems within the combustor as the cooling air temperature is the receiver outlet temperature. An associated problem might be fuel injector gumming because of thermal decomposition of the fuel in the internal lines.

If the full airflow is admitted to the combustor during augmentation then the problem of low combustor pressure drop will be avoided, however, the lean limit may still not be low enough to avoid undesirable steps during combustor ignition and shut-down. In this case variable-geometry and/or fuel staging will be required as in the case of the parallel system.

**Preferred Combustor Arrangement.** After studying the characteristics of both the series and parallel combustor arrangements, STI's preference is for the parallel arrangement. The parallel arrangement requires the development of a combustion system that
more closely resembles the existing standard production design thus STI believes this to be the lower risk path in terms of obtaining a reliable system within a given development effort. Because of the conventional inlet conditions all of STI's combustion system background is directly relevant to the application. The development of the high inlet temperature series combustor system is certainly technically feasible, however, the development path must be considered to be higher risk.

The preferred arrangement is shown schematically in Figure 9. The main features are as follows:

- **Control Valves**
  A separate control valve is used upstream of both the combustor and the solar receiver.

- **Torch Igniter**
  A torch igniter is used for combustor ignition. This would be continuously operating to ensure rapid reliable ignition at any combustor inlet conditions.

- **Combustor**
  The combustor is based on the standard production design and uses the VAB concept. Fuel staging is used with dual reaction zone air inlet swirlers. External variable geometry is accomplished by separating the reaction and dilution zones of the combustor by a bulkhead and controlling the airflow split with an external butterfly valve.

![Figure 9. Preferred Combustion System](image)

The control system analysis was made after having adopted the guideline of assuming that a "hard grid" or "infinite bus" would be the effective generator load. In this mode the gas turbine-generator speed is fixed by the grid frequency and load is selected by the operator. Rapid transients and the corresponding requirements for high response valves, fuel system components and combustor components are thus minimized.

**System Requirements.** The very slow response of the solar receiver in the cycle presents a number of serious problems when operating a gas turbine-generator. In order to safely control speed and load, standard fossil-fueled engines can vary the energy into the turbine in a fraction of a second. If this energy is supplied at a rate sufficient to maintain the generator at a high load torque and the load is lost (open circuit breaker), the engine and generator, without the restraining torque imposed by load, will accelerate at a rate determined by rotational inertia. In the case of the Centaur, if thermal heat energy is supplied to the turbine for more than a second, damage to the engine is probable. Acceleration rates are in the order of 3,500 rpm/sec resulting in a 25 percent overspeed in approximately one second for the single-shaft machine. On a split-shaft engine, accelerations will be considerably greater requiring faster response valves and lower stored energy to prevent damage. Protection of machinery against overspeed thus becomes the first priority.

Another high priority consideration is the protection of the turbine inlet ducting, nozzles and blades from inadvertent overtemperature. Long life with high reliability is ensured by maintaining the turbine inlet temperature at 1144 K (1600 F) or lower.

Protection of the solar receiver and its ducting from overtemperature is also an important consideration that requires an optimized controls strategy. If final overspeed or temperature protection for the turbine uses a dump valve, the placement of such a valve in the system has several tradeoffs. If only the turbine is to be considered, placement of the dump valve in the "cold" ducting would probably serve the purpose. However, the solar receiver would have reduced "cooling" flow and might possibly require a high response mirror defocusing system or other optical controls to protect against overtemperature.

Start-up and synchronization will be accomplished with a liquid fueled combustor. In the solar following mode no fuel burning except a small torch igniter is desirable. To hold a given load greater than the solar receiver input power the combustor will be ignited.

The above system requirements can be summarized as follows:

- Positive overspeed protection required for inadvertent load loss (circuit breaker trip).
- Turbine inlet temperature control to 1144 K (1600 F) or lower.
- Overtemperature protection of solar receiver must be integrated with turbine controls.
- Independent generator operation not required; except for start-up and shut-down.
- Load following (at energy input requirements above solar receiver level) will be provided by igniting the liquid-fueled combustor.

**Single-Shaft Versus Split-Shaft Recuperative Centaur.** All of STI's production experience with generator sets has been with simple cycle single-shaft machines. At present, development work is in...
progress to use a Mars split-shaft machine for generator sets. However, this new machine has seven stages of variable compressor stator vanes designed to modulate over a wide load range. By scheduling these at part loads the gas producer can be maintained at constant speed and thus the "stiffness" of a single shaft machine required for independent generator operation. Without inlet guide vane control (the Centaur inlet guide vanes are at present rated only for the start cycle) a considerable added lag is imposed in load making it undesirable for independent operation. When connected to an infinite bus only the inadvertent "open circuit" transient case causes serious control problems for the split-shaft machine. Start-ups and synchronization are also more difficult with split-shaft machines.

The study did not consider the possibility of using the compressor inlet guide vanes for speed control purposes on the recuperative Centaur as the development of such an operating mode would involve a lengthy experimental development program with the probability of extensive compressor redesign.

Series Versus Parallel Combustor. No basic changes in control strategy are required when considering the two options of the combustor in series with or in parallel with the solar receiver.

Engine start-up is accomplished using the liquid-fuel combustor which takes the unit to idle speed (split-shaft) or no-load conditions (single-shaft). Gradual focusing of the heliostat field with progressive transfer of the airflow to the solar receiver will be used to change over to full solar input. Load increase is sensed by speed drop. Initially the liquid-fuel combustor will be used to restore equilibrium, subsequent refocusing of the heliostats will reduce the combustor input until full solar operation is again established. Unloading would also be sensed by speed. Fuel would be cut if the engine is operating on partial combustor input otherwise air is initially bypassed through the combustor while the heliostat field is de-focused. After de-focusing the bypass air is reduced.

Control Concept Conclusions. Both series and parallel combustor arrangements could be controlled as either single-shaft or split-shaft recuperative Centaur generator sets. Both configurations are difficult to control as independent generator sets due to the slow response inherent in large valves. Independent operation would probably require a minimum amount of continuous fuel burning to regulate speed. The reliability of independent operation would also be questionable since the large hot air valves would be required to continuously modulate. The system having the fewest unknowns and the greatest potential reliability would be a parallel combustor arrangement on a single-shaft recuperative Centaur.

The eventual successful demonstration of the pilot plant will require integration of the engine control system with the heliostat field control. In addition, the engine control system will be required to deal with a greater number of control parameter inputs due to the more involved nature of the auxiliary combustion system and the requirement to run the solar receiver at specified outlet temperature conditions.

Because of the increased complexity of the engine control a microprocessor based system appears to be well suited for the application.

STI has a significant background in the use of microprocessor-based controls. Based on STI's control system background, the following remarks regarding microprocessor controls can be made:

- A microprocessor-based control system could be developed for less cost than the equivalent analog system.
- Microprocessors offer greater versatility in pursuing the logic of a complicated control system such as will be the case in the application under study.
- Real-time changes can be made to the control system if external adjustors are available.
- After-the-fact development changes in control logic can be made at minimal expense since these are only software modifications.
- Several control scheme options can be made available on-line by programming different control circuitry chips.

Valves

Special valving requirements are associated with either the parallel or series receiver-combustor systems for splitting the airflow between the two components. For the parallel receiver-combustor arrangement, a separate valve upstream of the combustor and the receiver would be exposed to the recuperator outlet conditions which at the engine design point are approximately 7.5 ata (110 psia) and 706 K (810 F). The valve would be required to seal with minimum leakage in the closed position and modulate between closed and open positions with minimum pressure drop in the full open condition. Standard butterfly valves are available on the market to cover this type of duty. For a full-open pressure drop level less than one percent (1.0%) of upstream pressure, a valve size of approximately 40.6 cm (16 in.) in diameter will be required.

A series receiver-combustor arrangement can be envisaged in which no control valves are required. In order to avoid the parasitic pressure drop of the combustor, however, when operating on only solar input, a low pressure drop high temperature valve is required to bypass the combustor. This valve would be required to modulate over a wide flow range to avoid large step outputs from the combustor when ignited and would be exposed to the maximum design turbine inlet gas temperature of 1144 K (1600 F).

High temperature modulating valves were discussed with several vendors and no off-the-shelf units are currently available. Material substitutions would be required with specialized local cooling schemes for the valve bearings. Delivery times of up to one year are quoted and it is apparent that any high temperature control valve would need to be evaluated in bench tests and might require considerable development time.
A hot dump valve situated upstream of the turbine inlet would not be a problem if the operation of such a valve could be considered as only "on-off" and used as an emergency shut-down. In this case a rupture disc type of valve activated by either a pneumatic ram cutter or an explosive charge can be employed. After engine shut-down the valve would be "re-built" which could be a fairly minor procedure with minimum down time.

PREFERRED ENGINE SYSTEM CONFIGURATION

An assessment of the combustion and control system options within the constraints of the study guidelines leads to a preferred engine system configuration consisting of a single-shaft recuperative Centaur generator set with the following major features:

- A liquid fuel combustion system in parallel with the solar receiver
- Modulating butterfly valves upstream of both the combustor and the solar receiver for control purposes
- A flow dump valve situated between the combustor/receiver and the turbine inlet for emergency engine overspeed protection in the event of a circuit breaker trip at partial or full load conditions
- A microprocessor-based electronic control system for start-up and shut-down scheduling, load control and emergency protection.

CONCLUDING REMARKS

- System Configuration. As a result of the study STI feels that a single-shaft, recuperative Centaur generator set with a parallel liquid-fueled combustion system arrangement is the optimum selection for the pilot plant within the limitations of the study guidelines.

- Test Cell Demonstration. A satisfactory test cell feasibility demonstration of the engine system configuration could be accomplished by simulating the solar receiver with a second combustion system controlled to reproduce the same time-outlet temperature characteristics.

- Bench Scale System Investigations. Before a test cell demonstration of the modified recuperative Centaur engine can be attempted an intermediate phase of small-scale rig testing is recommended for the combustion system where the technology void is such that a full-scale design has a low probability of satisfactory operation without a screening and development phase. This would be carried out in a reduced size range for cost effectiveness.

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