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345 E 47 St., New York, N.Y. 10017

S. C. Kuo
Chief,
Energy Systems
Mem. ASME

T. L. O. Horton
Systems Engineer
Mem. ASME

H. T. Shu
Systems Engineer

United Technologies Research Center,
East Hartford, Conn.

The Prospects for Solar-Powered Closed-Cycle Gas Turbines

This paper presents the results of a systems study to evaluate the technological and economic feasibility of utilizing closed-cycle gas turbines integrated with an advanced-design central receiver for solar power generation. Applicable turbomachinery technologies were reviewed to estimate their future advances expected. System design-point performance, component size, and cost characteristics of closed-cycle air turbines were estimated, and system operational and control characteristics, including off-design and part-load performance characteristics, are discussed. Critical system components were reviewed to estimate the appropriate testing and development time and cost schedules required.

ABSTRACT

This paper presents the results of a systems study to evaluate the technological and economic feasibility of utilizing closed-cycle gas turbines integrated with an advanced-design central receiver for solar power generation. Applicable turbomachinery technologies were reviewed to estimate their future advances expected. System design-point performance, component size, and cost characteristics of closed-cycle air turbines were estimated, and system operational and control characteristics, including off-design and part-load performance characteristics, are discussed. Critical system components were reviewed to estimate the appropriate testing and development time and cost schedules required.

INTRODUCTION

Closed-cycle gas turbine (CCGT) power conversion systems have been studied, built, and operated for over forty years, mostly in Europe and a few in Japan (Refs. 1 and 2). A variety of factors have contributed to prevent a widespread implementation of CCGT systems during this period of time. In the early stage of CCGT development, the maximum cycle temperature was limited to approximately 649°C which restricted the CCGT power generation efficiency to a level which was not attractive enough to replace the Rankine systems. Later, as material capabilities were improved to allow increased CCGT maximum cycle temperatures, the availability of low-cost and clean hydrocarbon fuels made the CCGT system (which required an indirect heater) less attractive than open-cycle gas turbines (OCGT) which expand combustion gases at higher temperature levels directly through the turbomachinery. Furthermore, the OCGT offers the possibility of combining with a steam system (COGAS) to convert the thermal energy from fuel combustion more efficiently into mechanical or electric power.

The impending decline in availability of high quality fossil fuels and increasing interest in other non-fossil heat sources, such as solar thermal energy, present new opportunity for CCGT applications. The OCGT is not well suited (in the current state-of-the-art) to burning poor quality fuels, and if an external gas heater is used (i.e., a lower turbine inlet temperature) a recuperator is often needed to achieve an acceptable thermal efficiency. The cost of such recuperators is directly related to the pressure and temperatures of the gases being utilized; the hot-gas of an OCGT recuperator is always at low pressures (close to atmospheric), thus resulting in bulky and costly units. The CCGT, on the other hand, can significantly increase the minimum operating pressure in the recuperator and hence lower the size and expenditure needed for the recuperator as shown in Fig. 1. Furthermore, the precooler requirement in a CCGT system can be considered an advantage rather than a detriment. The hot water produced by the precooler (which operates with higher pressure gas than an OCGT waste heat recovery unit and higher heat rejection temperatures than a condenser in a steam

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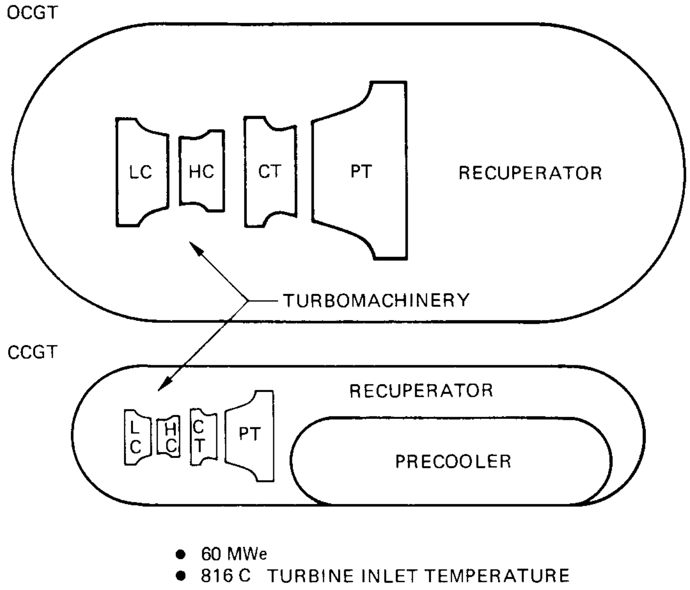


Fig. 1 - Comparison of Open- and Closed-Cycle Air Turbine Component Sizes

power plant) can be utilized to provide heat for a variety of residential and/or industrial uses, thus offering an attractive cogeneration function. It would then appear that some of the factors which have held back CCGT implementation (external heater, and requirements for additional heat exchangers) may be regarded as potentially attractive attributes in the future. Excellent power conversion and cogeneration efficiencies are offered by the CCGT while a variety of heat sources are possible, ranging from solar thermal energy to poor quality fossil fuels or even nuclear energy. The prospects for the CCGT when integrated with the solar heat source for electric power generation are discussed in the sections which follow.

CLOSED-CYCLE GAS TURBINE TECHNOLOGIES

The technologies needed for utilizing closed-cycle gas turbine (CCGT) systems for utility power generation already exist. Many CCGT power systems have been successfully operated using air, helium, nitrogen, argon or other gases as the working fluid (Refs. 3, 4, and 5). Unit capacities have been demonstrated from a few kilowatts to 50 MW. Design studies have indicated that units which produce several hundred megawatts are feasible (Ref. 6). Thus the full range of output capacities which have been considered for solar power plant designs (Ref. 7) are compatible with closed-cycle gas turbine systems. Whether the solar plant utilizes a large central receiver or a small dispersed parabolic dish collector, closed-cycle gas turbines are suitable for the power conversion subsystem.

In terms of increasing the maximum cycle temperature, closed-cycle gas turbines are limited by the same material temperature capabilities as open-cycle gas turbines, as shown in Fig. 2. In comparison to vapor-cycle (e.g. steam) power conversion systems, the cycle temperature for CCGT is not limited by critical operating temperature restrictions of the working fluids. However, closed-cycle gas turbine systems always require an external heater, a characteristic which is a disadvantage in terms of achieving higher turbine inlet temperatures for any fossil-fueled application. However, all solar thermal power systems must include an external heater (receiver) regardless of the power conversion system used, a fact which dictates that both open- and closed-cycle gas turbine systems are limited to the same maximum cycle temperature. If superalloys are used in the gas heater, the maximum allowable gas temperature will be approximately 820°C (Ref. 8). When ceramics become available, the maximum gas temperature for both open- and closed-cycle designs might be increased to 1100°C or higher. This higher gas temperature would allow substantially higher conversion efficiency if parasitic losses can be kept reasonably low. The application of ceramic technology to solar receivers (Ref. 9) must also overcome barriers in piping, ducting and insulation before a gas turbine can be integrated with these higher temperature receivers for efficient operation. It must be mentioned that, although aircraft gas turbines routinely exceed a maximum cycle temperature of 1100°C, extensive cooling air flows (provided by the compressor) are used to protect the superalloy metals in these engines. Such cooling practices are not realistic in an external heater, or when the heater is far removed from the turbomachinery, thus dictating that heater and ducting components will have

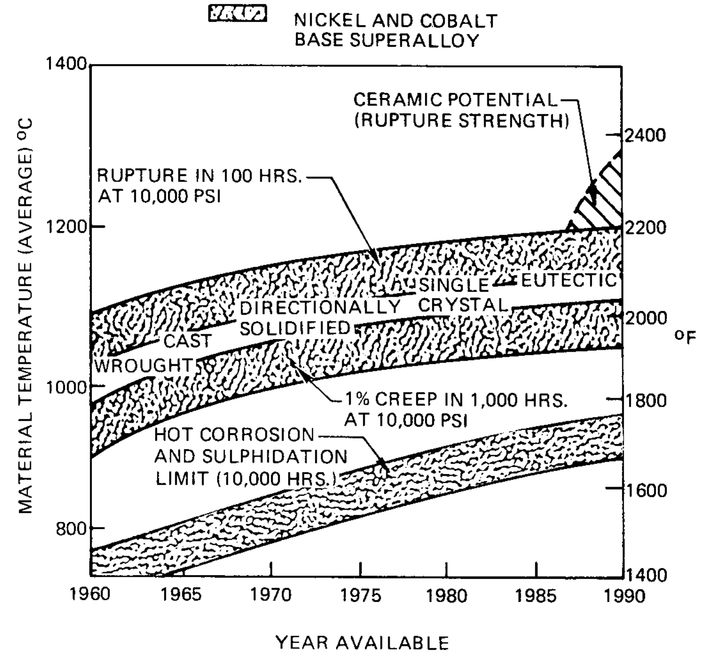


Fig. 2 - Advances in Hot Section Material Properties

to be made of ceramics (or yet undeveloped high-temperature alloys) to increase maximum cycle temperatures over 820^{o}C. A projection recently made at UTRC for the progression of turbine inlet temperatures for closed-cycle gas turbines (Ref. 10) is shown in Fig. 3. As can be seen in this figure,

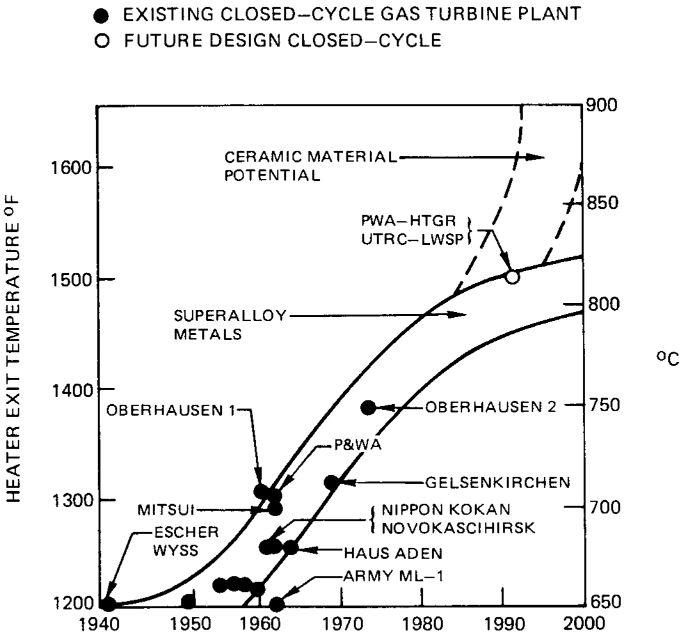


Fig. 3 - Projected Closed-Cycle Gas Turbine Maximum Temperature Progression

ceramics are projected to become available for stationary parts of CCGT systems around 1990, just as the first commercial solar power systems are expected to be put "on-line." The timing of these developments will bear close observation.

Closed-cycle gas turbine systems do not provide the broad inventory of "off-the-shelf" integrated system capacities which are available for steam systems. However, the potential for adapting existing open-cycle equipment to CCGT applications (with reasonable modifications) should not be ignored. Among the innumerable open-cycle gas turbines built and operated in the past 40 years (Ref. 11), many have operated at extremely high pressure levels (such as military supersonic aircraft engines) and/or at large mass flow rates or power levels (such as the GE 9000 or UTC FT-50). Machinery such as this could be used in conjunction with appropriate ducting (and possibly a recuperator) to provide open-cycle gas turbine power generation for many of the solar power plant sizes considered to date; or to provide closed-cycle gas turbine power generation when joined with well developed heat exchangers (such as shell and tube designs) which will recuperate and precool the working fluid prior to re-entering the compressor. In comparison to existing steam-cycle equipment, the assembly of closed- or open-cycle systems for existing equipment may encounter more problems associated with matching the components to each other; however, both steam or gas turbine systems should be expected to encounter development problems in matching the often remotely located solar-thermal receiver with the remainder of the power conversion system.

Other important technological considerations are the methods and requirements for transporting solar thermal heat to, and rejecting waste heat from, the power conversion system. Closed- or open-cycle gas turbines can circulate the working fluid directly through the solar receiver or use an intermediate heat transfer fluid (such as liquid metal or salt) to transport the heat from the solar receiver to the working gas heater. The former method must be given careful attention to minimize pressure losses while the latter must consider the technological problems (such as corrosion, circulation, complexity and safety) which have been identified in years of previous development in nuclear power concepts. In dealing with the heat rejection required from the power conversion systems, the closed-cycle Brayton systems offer considerable advantages over the Rankine power systems; the former can reject waste heat at a higher temperature level, as high as 175^{o}C above the constant condenser temperature used in a Rankine system. The high-temperature waste heat can be utilized more effectively for industrial or residential heating if desired. Furthermore, use of dry cooling towers will be economically more realistic for the closed-Brayton system because of drastically reduced tower size attributable to significantly higher log-mean temperature difference in the cooler as compared with the steam power systems.

PERFORMANCE CHARACTERISTICS

Extensive analyses have been made in recent years (Refs. 7 and 12) to estimate the performance characteristics of closed-cycle gas turbines for solar thermal power generation. Results of these studies indicate that power conversion system efficiencies over 40 percent would be attainable without using high-temperature ceramic receivers (Fig. 4). The recuperated and intercooled configuration (shown in Fig. 5) associated with this performance is just one of many possible alternatives for closed-cycle gas turbines, but Fig. 4 shows the representative level of design-point performance possible with the CCGT. Recuperation is the most critical aspect of the configuration shown in Fig. 5. The performance of a recuperated closed-cycle gas turbine which uses air as the working fluid will be comparable to a recuperated open-cycle configuration. While the higher pressure levels used in a closed-cycle gas turbine contribute little to improve conversion efficiency, they can significantly reduce the size of the recuperator and other heat exchangers as well as the turbomachinery for a potential cost benefit.

If helium were used as the working gas, the maximum CCGT efficiency levels may not change appreciably (Ref. 13) whereas the pressure ratio (around 3 to 1) required to obtain this maximum efficiency will be lower than the 4 or 5 to 1 ratio needed for the air cycle system. The major benefit

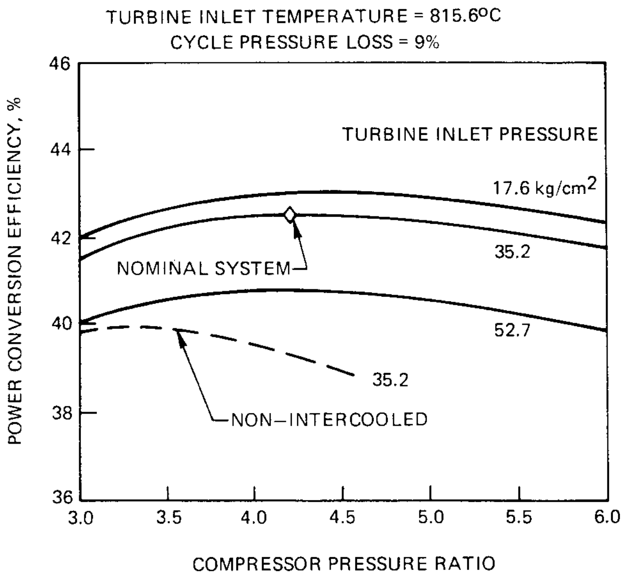
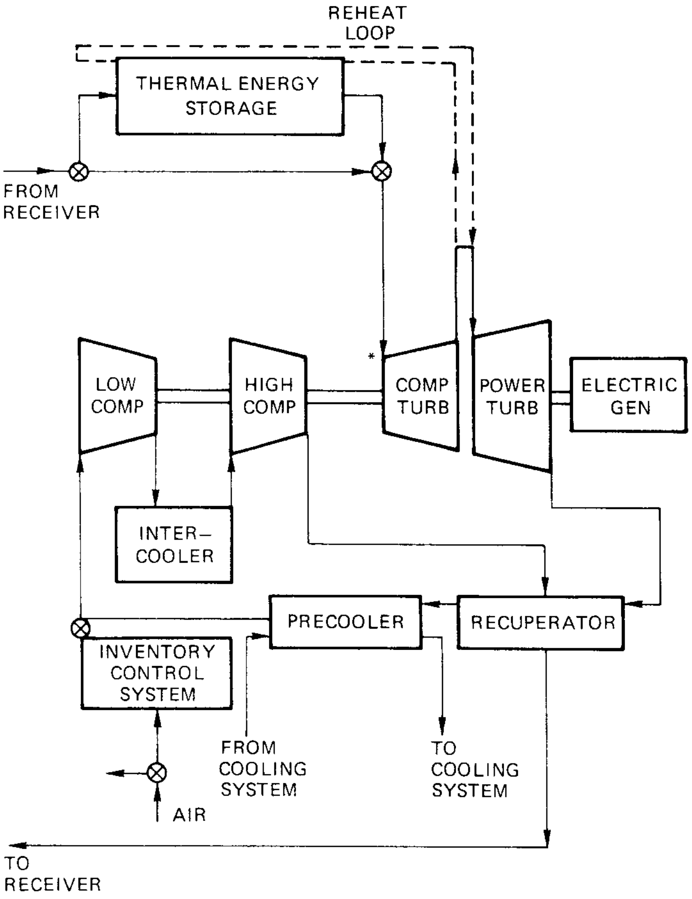


Fig. 4 - Effect of Compressor Pressure Ratio on Power Conversion Efficiency



*NOMINAL TURBINE INLET
TEMPERATURE = 815.6°C
PRESSURE = 17.6 TO 52.7 kg/cm²

Fig. 5 - Schematic Diagram of Closed-Cycle Air Turbine Solar Power Conversion System

of using helium will be to reduce the size of the heat exchangers still further due to better heat transfer characteristics of helium compared to air. This last effect will affect the solar plant performance through the receiver design requirements. A smaller receiver might be more efficient due to changes in factors such as heat loss, re-radiation and optical flexibility.

Possibly even more important for a solar power plant is the performance of a CCGT when operated with reduced power input because this is liable to occur frequently in a solar-powered system. Closed-cycle gas turbine systems can provide almost unchanged power conversion efficiency over a broad range of output (from approximately 100 percent design power on down to only 20 percent of the design point conditions). This characteristic has long been known and was analyzed in detail in recent work performed under DOE contract (Ref. 12). The CCGT efficiency characteristic shown in Fig. 6 results from the use of a process called "inventory control." This process can be compared to the condition encountered by gas turbines which power airplanes from a sea-level operating condition to a high altitude condition. During this climb, the air density is continuously decreasing and the flow rate through the engine will decrease, as will the output power. Furthermore, it is possible for the high altitude cruising condition to provide a fuel efficiency which is equal to or better than efficiency at maximum power.

- DESIGN POINT OUTPUT POWER = 75 MWe
- DESIGN POINT POWER CONVERSION EFFICIENCY = 41.9%

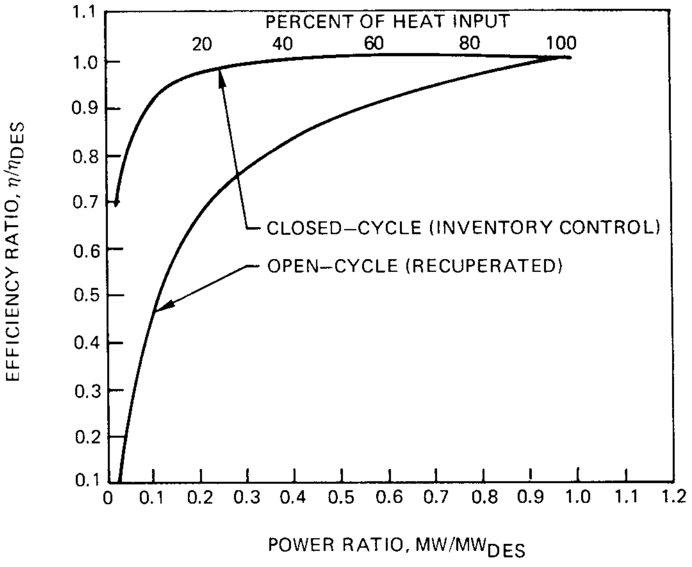


Fig. 6 - Closed- and Open-Cycle Air Turbine Part-Load Performance Characteristics

A gas turbine operating in a closed-cycle can experience conditions and performance characteristics similar to that of the airplane engine. When less than rated power is desired in a CCGT, the inlet pressure to the compressor can be reduced from the rated conditions by discharging the working gas to storage tanks, thus reducing the mass flow through the gas turbine and hence the output power. The "inventory" of air mass within the closed loop is thus reduced. When changes are made in this manner, the operating point on the gas turbine component "operating maps", such as the one shown in Fig. 7 will remain relatively unaffected over a broad range of flow (and power) variation. Therefore, the component efficiencies and pressure ratios remain almost unchanged. If the maximum cycle temperature is held constant, the overall cycle conversion efficiency will then also remain basically unchanged. However, when the flow rate is reduced below 20 percent of the rated value, other effects such as frictional losses and enlargement of the boundary layers can cause significant component efficiency degradation. However, the reduced pressure loss in ducts and heat exchangers (as flow rate is reduced) tend to improve cycle efficiency, and therefore, compensate for part of these losses over a portion of the power spectrum. The achievement of a part-load efficiency which is higher than the efficiency at maximum rated power might even be accomplished by a careful "matching" of gas turbine components and concurrent variation of maximum cycle temperature as power is reduced.

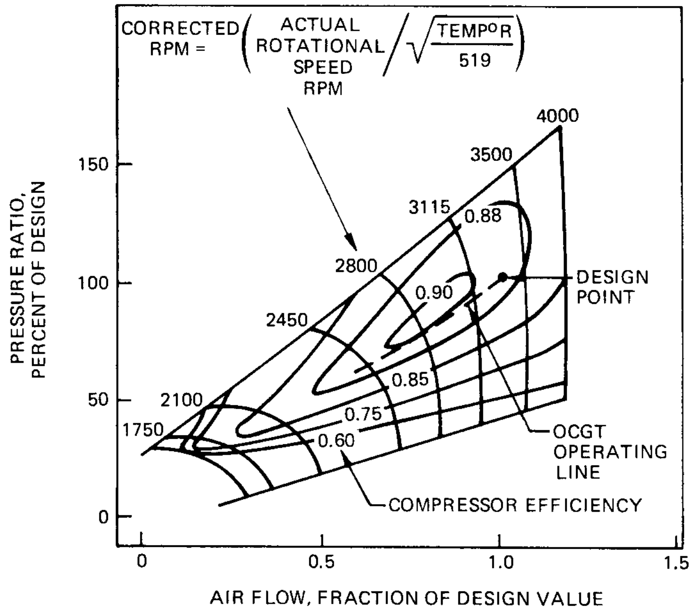


Fig. 7 - Typical Compressor Operating Map

The flexibility of CCGT systems in providing a multitude of relationships between input and output power is unrivaled. Steam systems, particularly in Naval applications, have varied steam pressure (inventory) in an attempt to improve part-load performance, but have encountered some operational problems. For example, CCGT systems are free from partial steam condensation in turbine sections and the associated erosion damage.

Some of the off-design and part-load characteristics for a solar-powered CCGT are summarized in Figs. 8 and 9. As can be seen, the CCGT is operable over a wide range of maximum cycle temperature and pressure conditions. This means that early morning and late afternoon (or cloudy day) solar insolation might be more completely utilized in the CCGT in comparison with steam or open-cycle gas turbine systems. Over a period of one year, these as yet uncredited characteristics (past analyses often ignored solar input in early morning and late afternoon), might significantly improve the total yearly power output (or reduce storage requirements) and thus make solar power generation more economically attractive.

An area of CCGT performance which should be given more attention is the capability to provide both power and heat generation. Recent DOE sponsored evaluations of cogeneration technologies (Ref. 13) have shown that the CCGT is a fairly attractive alternative for improving fuel economy for fossil fired power plants. Similarly, solar energy must be utilized efficiently to reduce its effective energy cost. In this regard, the CCGT appears to offer an even greater potential because of its simplicity and

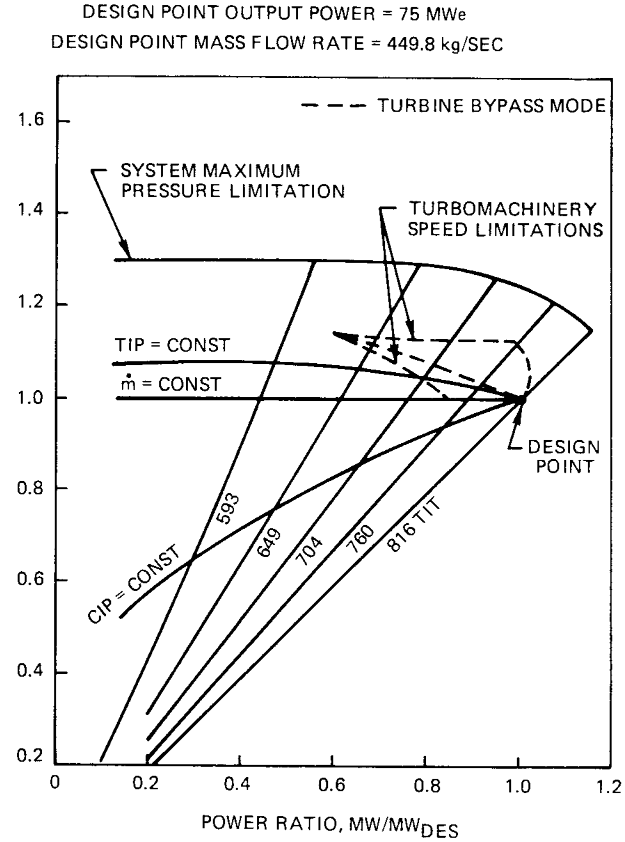


Fig. 8 - Flow Rate Characteristics of Part-Load Operation by Various Control Schemes

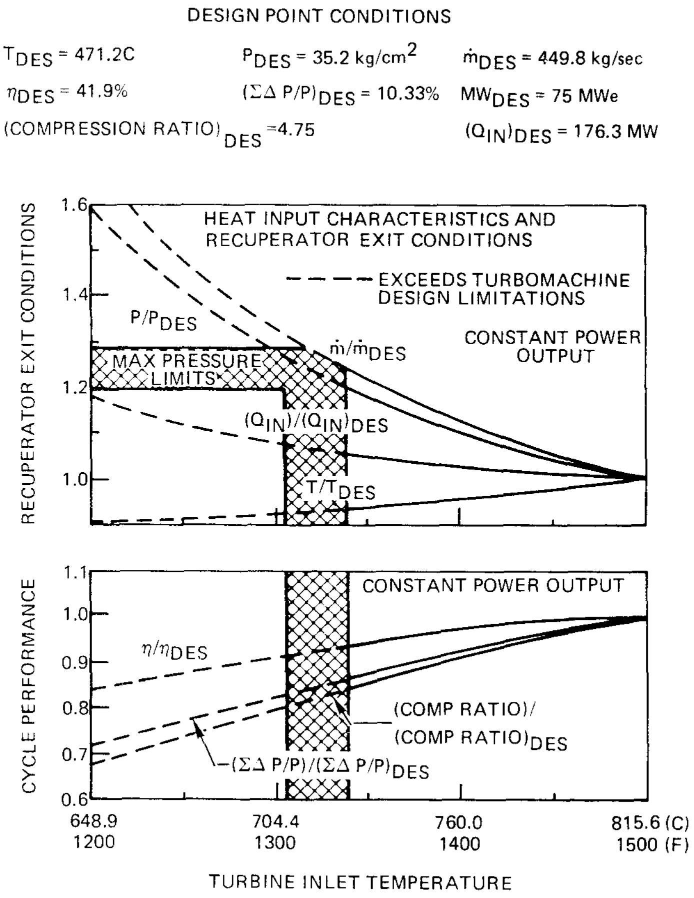


Fig. 9 - Off-Design Performance for Variable Turbine Inlet Temperature and Constant Power Output

compatibility with the receiver and waste heat rejection systems which can provide efficient utilization of solar thermal energy. Additionally, when district/process heating is considered, the waste heat temperature capability of CCGT systems would seem more attractive than either steam or combined gas and steam systems.

DEVELOPMENT REQUIREMENTS

The development requirements for closed-cycle gas turbine systems have often been considered to be large, particularly in comparison to steam systems. Unfortunately, CCGT planners seem to be in the unenviable position of dealing with a technology which is well developed but not yet extensively implemented. As a result, the planners are smart enough to know where the problems will be, but not totally sure of the answers for these problems. In comparison with a new technology whose real-world problems have not yet been realized, or an old technology which has solved the same problems many times, the CCGT system often appears to require significant development expenditures. This may be attributed to the fact that the CCGT planners are being overly cautious or not optimistically projecting the possible incorporation of existing technologies.

Realistically, CCGT systems, or any new-design gas turbines, are not expected to operate flawlessly upon initial start-up. In particular, not enough is known about control systems for a solar-powered CCGT to avoid a myriad of minor problems which could cause major delays and expenditures for the first demonstration plant of a given configuration and capacity. It can be said that even a solar plant which merely integrates existing steam equipment can be expected to encounter similar problems (although more easily and cheaply solved). In comparing development options and systems alternatives, careful attention should be given to weigh the potential of new concepts versus older designs which will provide a more expedient demonstration. Unfortunately, the resolution of such considerations have not always been based on consistent engineering judgment.

When estimating the development requirements for solar-powered CCGT systems, several factors must be considered. The solar energy receiver will be a totally new design and hence must be expected to be a major development item. Extensive testing and development must be expected before any receiver concept (metallic or ceramic, air-, steam-, or helium-cooled, etc.) can be expected to provide operational characteristics and reliability which meet the utility standards. Many design concepts for solar receivers remain to be tested. There are direct and indirect solar radiation impingement designs. There are free hanging tubes and spring loaded tube concepts to be selected. There are aperture geometry and re-radiation losses to be considered. Of course, the diurnal thermal cycle imposes a stringent requirement which far exceeds conventional boiler design conditions. Even the insulation concepts may encounter unexpected problems due to the desire to achieve a high receiver efficiency with high exit temperatures, and the inability to cool the walls in the same manner as in conventional steam power plants. It must be mentioned that steam -boiler design made many advances in the first 20 years of this century, and that solar receivers can also be expected to undergo a similar, though probably more compressed development process. It would appear that much development testing and years of experience are needed before solar receivers attain the same level of technological maturity as conventional steam boilers. In addition, solar receivers for CCGT systems will probably be larger than receivers for systems which circulate high pressure steam or liquid metal (or salt). This is due to the high heat transfer coefficients possible with the latter systems which should allow smaller areas for heat transfer from the solar radiation to the working fluid.

It must also be decided whether the closed-cycle turbomachinery should be a totally new design or should be based on adaptation of existing open-cycle components instead. If the latter case is selected, the amount of adaptation must be carefully selected in order to attain maximum cost savings without sacrificing the system reliability. If overall system parametric design and cost evaluations indicate that the requirements for CCGT turbomachinery cannot be met by using existing components, then a significant development effort will be required. The development of new machinery which uses air as the working fluid should require less time and effort than new helium turbomachinery, because of the extensive test data available from air systems to predict component and sub-component performance. A typical "success-oriented" development effort for a new air turbomachine (CCAT) is identified in Fig. 10 and the limited projected expenditures for such a program are shown in Table I. These projections are based on design and development efforts directed toward demonstration of existing technology for solar power applications, and therefore should be regarded as a "bare bones" effort without new technological development.

	TASK	COST
1.0	FULL SCALE TURBOMACHINE AND POWER TURBINE	$61.85
2.0	COMPONENT DEVELOPMENT	39.91
3.0	CONTROLS	3.28
4.0	MANAGEMENT	2.17
	TOTAL	$107.21

NOTES: COST ESTIMATES:

1. MILLIONS OF DOLLARS
2. BASED ON 1978 CONSTANT YEAR DOLLARS
3. INCLUDES G & A AND FEE

Table I - CCAT Cost Breakdown by Major Task

A lower cost turbomachinery development program would be possible if existing turbomachinery components were adapted to a closed-cycle application. For example, many advanced industrial gas turbines similar to a GE 9000 or UTC FT-50 could provide a compressor and turbine unit (high spool) for a 40-MWe recuperative closed-cycle power conversion system. In the case of FT-50, this would be accomplished by extracting the high compressor and high turbine from the unit to provide a pressure rise from 4.6 kg/cm^2 (65 psia) to 17.6 kg/cm^2 (250 psia) without major redesign. Higher operating pressures (and more output power) can be obtained if more extensive redesigns (on casings, structural support, and bearing compartments) were made to accommodate the higher pressure levels. In comparison, open-cycle designs could use the large number of existing industrial gas turbine designs to provide over 80-MWe output at 800^o C turbine inlet temperature but would have to sacrifice thermal efficiency significantly since these machines are not designed for recuperation. Combined gas and steam cycle configurations could provide even higher output levels but would require higher maximum cycle temperatures to achieve the same efficiency possible with recuperative closed- or open-cycles.

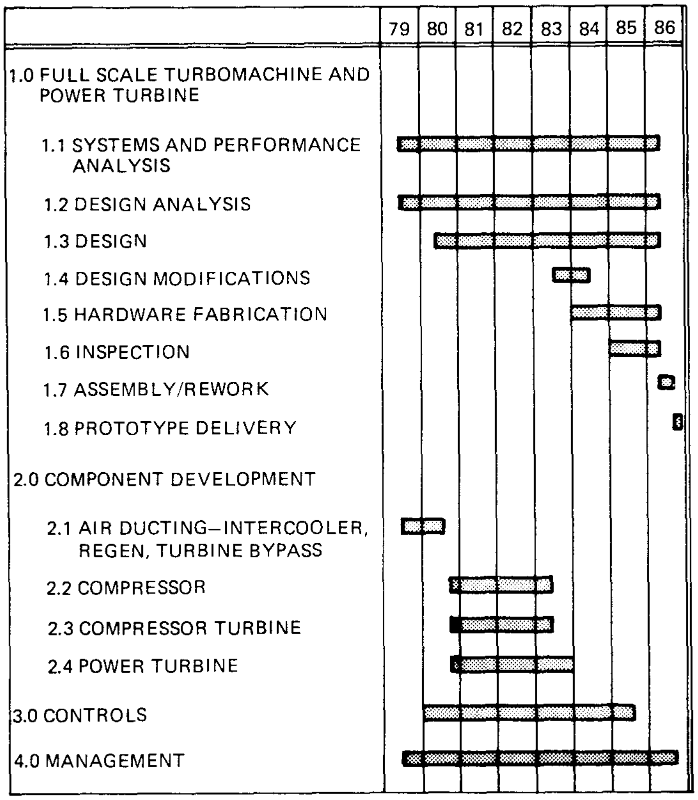


Fig. 10 - CCAT Development and Test Schedule for Commercial Installation Readiness

The selection of heat exchangers needed is also an important consideration. However, the use of untried heat exchanger concepts would seem unnecessary because both the shell and tube type and more compact plate-fin designs have already been proven (Ref. 14). Probably the most unpredictable characteristics of the heat exchangers are the pressure losses experienced at the entrance and exit sections of the modules. Sub-scale testing should be conducted to identify these characteristics to ensure that they are compatible with the total cycle pressure loss limitations.

The available open-cycle air turbomachinery can thus provide a significant portion of the components needed for CCGT units with output levels which cover most of the range identified for solar electric power plants (Ref. 7). The relative sizes for such turbomachinery estimated to provide 40 to 100 MWe are shown in Fig. 11 in comparison with the FT-50 open-cycle engine. It was found that when used in a recuperated closed-cycle configuration, the existing open-cycle machinery might provide output up to 40 MWe without major change, or up to 100 MWe with increased pressurization. The use of air as the working fluid for the CCGT might therefore minimize turbomachinery development effort by using OCGT technologies and components, while still allowing near optimum conversion efficiency. Such equipment would then allow solar thermal programs to concentrate on demonstrating and developing the more unique solar receiver technology.

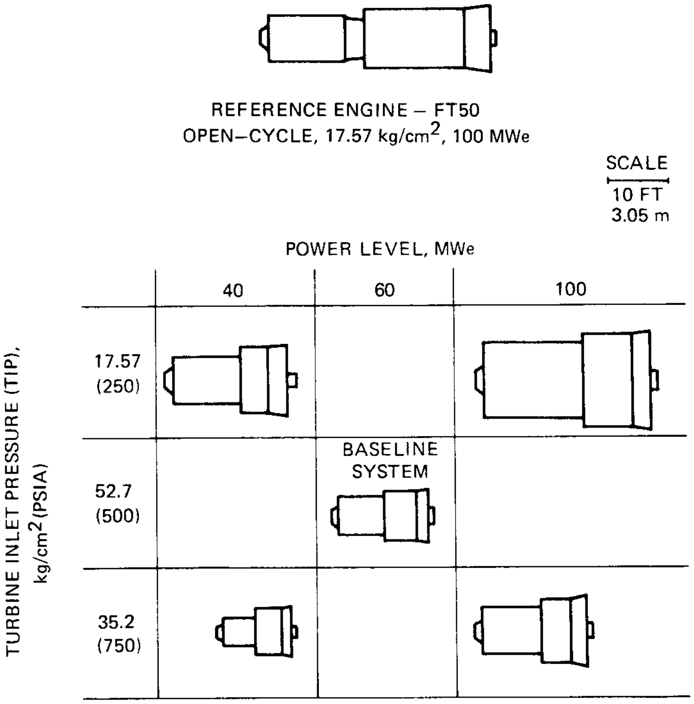


Fig. 11 - Parametric Turbomachinery Sizing Results, Compared to FT50 Engine

CONCLUSIONS

Closed-cycle gas turbines using air or helium as the working fluid offer the potential of efficient solar electric power generation when integrated with the advanced central receivers of gas-cooled designs. The performance capability of the solar-powered CCGT system will be limited by the temperature capability of the solar receiver which is approximately 1500°F (816°C) for metallic receivers, or nearly 2000°F (1094°C) for future ceramic receivers. Using a metallic receiver with a reasonable recuperation level, the range of power conversion system efficiencies is between 38 and 44 percent for output capacity levels of between 40 and 100 MWe respectively.

The CCGT systems suitable for central receiver solar plant applications do not require new technologies. However, a lower cost turbomachinery development program utilizing existing gas turbine components (with appropriate modifications) adapted to a closed-cycle application would require seven years and total expenditures of approximately $100 million to build and test the first unit for practical solar power generation.

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