NASA-TM-82736

NASA Technical Memorandum 82736

Parametric Performance Analysis of Steam-Injected Gas Turbine with a Thermionic-Energy-Converter-Lined Combustor

Yung K. Choo and Raymond K. Burns
Lewis Research Center
Cleveland, Ohio

February 1982

NASA

PARAMETRIC PERFORMANCE ANALYSIS OF STEAM-INJECTED GAS TURBINE WITH A THERMIONIC-ENERGY-CONVERTER-LINED COMBUSTOR

Yung K. Choo and Raymond K. Burns

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio

E-1048

SUMMARY

This study was conducted to analyze the performance of steam-injected gas turbines having combustors lined with thermionic energy converters (STIG/TEC systems) for a range of system design parameters. This system was devised to combine the advantage of steam injection of gas turbines with conversion of high-temperature combustion heat by TEC's. It was configured so that the TEC collectors are cooled by relatively low-temperature steam produced in an exhaust-heat-recovery boiler. The steam rises in temperature from the collector cooling, is injected into the stream of combustion products, and is expanded through the gas turbine.

For comparison, two baseline systems were also analyzed: a steam-injected gas turbine (STIG) and a combined gas turbine/steam turbine cycle. For consistency, common gas turbine parameters were assumed for all of the systems.

Injecting steam into a gas turbine combustor improves system performance over that of the simple-cycle gas turbine. When the TEC-lined combustor is added to the steam-injected gas turbine, both system efficiency and specific power (net power per kilogram (pound) of compressor inlet air) are further improved. One performance advantage of the STIG/TEC system is that it achieves its highest efficiency at the highest specific power.

Two configurations of the steam-injected gas turbine using a TEC-lined combustor were evaluated. One uses a single TEC stage. The other uses two TEC stages that are arranged along the combustor walls in series. The two stages differ from each other by emitter and collector temperatures. Depending on the configuration and design parameters assumed, the STIG/TEC combustor systems achieve peak efficiencies of 39.3 to 42.3 percent. Specific power corresponding to the efficiency range reaches 206 W-hr/kg of air for the configuration using a single TEC stage and 230 W-hr/kg of air for the alternative configuration. The STIG system achieves its highest efficiency of 39.1 percent. The corresponding specific power is 120 W-hr/kg of air. The combined cycle has a maximum efficiency of 41.3 percent at a corresponding specific power of about 100 W-hr/kg of air.

INTRODUCTION

Several studies (refs. 1 to 6) have quantified the potential advantage of steam-injected gas turbine (STIG) systems over simple-cycle gas turbines and

N82-23678#

conventional combined gas turbine/steam turbine cycles. As in a combined cycle, the STIG cycle recovers exhaust heat to produce steam that is used to generate additional power. But, instead of being used in a separate bottoming cycle, the steam is injected into the gas turbine combustor and is expanded through the turbine along with the combustion products. The steam injection increases the gas turbine mass flow relative to the compressor airflow and increases the specific heat of the turbine flow relative to that for a simple gas turbine. Thus these studies have shown that the STIG system efficiency and specific power are substantially increased over that for the simple-cycle gas turbine. Since the steam-injected gas turbine does not require a separate steam turbine bottoming cycle, it has the potential for significantly lower capital cost than a conventional combined cycle for about the same efficiency.

Other studies (refs. 7 and 8) have quantified the potential gains in efficiency and power output for combined gas turbine/steam turbine cycles having combustor walls lined with thermionic energy converters (TEC's). A thermionic energy converter consists of a hot electrode (the emitter) facing a cooler electrode (the collector) with vacuum or a highly conductive plasma in a narrow gap between the two electrodes. When sufficient heat is supplied to the emitter, some of the high-energy electrons will obtain enough energy to escape from the emitter surface. Electrons flow from the emitter to the collector through the gap and deliver electric power to an externally connected load. In the systems studied in references 7 and 8, heat for the emitters is supplied from the combustion heat. The heat rejected from the TEC collectors then preheats the combustion inlet air to reduce fuel flow. Since the TEC's remove a part of the heat from the combustor, less excess air is required for a given turbine-inlet temperature, and thus compressor airflow is reduced. The result is a gain in overall system efficiency.

This study was conducted to explore the performance of a system that combines the potential performance gains of a steam-injected gas turbine and a TEC-lined combustor (STIG/TEC). A system was configured so that the TEC collectors are cooled by relatively low-temperature steam produced in an exhaust-heat-recovery boiler. After cooling the TEC's the steam is injected into the stream of combustion products and expanded through the turbine. The use of steam as the collector coolant was considered because it might improve the heat transfer and result in a smaller heat exchanger, and it might allow a lower collector temperature that would result in higher TEC efficiency. The steam injection might also help control thermal oxides of nitrogen by quenching combustor temperature.

Two different configurations were considered for the STIG/TEC system. The performance (efficiency and specific power) of two STIG/TEC configurations was analyzed for a range of heat exchanger parameters and compared with that of two baseline systems: a STIG system and a conventional combined cycle. The two baseline systems were also analyzed in this study. For consistent comparison, common gas turbine parameters presented in table I were assumed for all of the systems.

SYSTEM DESCRIPTION

Figure 1(a) is a schematic of a STIG system. Steam is produced in the exhaust-heat-recovery boiler from the heat in the turbine exhaust gas and is injected into the gas turbine combustor. In this system a small fraction of the compressed air is used for turbine cooling. Most of the air is used for combustion and to maintain the turbine-inlet temperature, which is specified as 1093° C (2000° F).

Figure 1(b) is a schematic of a combined gas turbine/steam turbine cycle. Heat is recovered from the gas turbine exhaust by using it to produce steam in the exhaust-heat-recovery boiler. The steam is then used to produce additional power in a separate steam turbine bottoming cycle. The bottoming-cycle configuration and parameters shown in the figure are similar to those of a steam cycle considered in reference 9. The steam throttle pressure of 2.31 Pa (335 psia) is well suited to the exhaust-heat-recovery boiler gas-side inlet temperature and to the steam turbine throttle temperature, which results from the parametric variation of the boiler approach temperature difference ΔT_{ap}.

Figure 1(c) shows the first of two configurations for the STIG/TEC systems. In this system the combustor is lined with thermionic energy converters. The TEC's generate electric power from combustion heat, which is at a higher temperature than the turbine-inlet temperature. Partial cooling of the combustion gases by the TEC's decreases the excess air required to reduce the temperature of the combustion products to the turbine-inlet temperature. The TEC collectors are cooled by relatively low-temperature steam generated in the exhaust-heat-recovery boiler. The steam is thus further heated in the collector cooler and then is injected into the gas flow stream. The TEC design parameters were taken from reference 10 and are presented in table II(a).

Figure 1(d) shows an alternative configuration for the STIG/TEC system. In this system two TEC stages are arranged along the combustor walls. They differ from each other by emitter and collector temperatures. The first, lower-temperature stage of TEC collectors is cooled by saturated steam from the exhaust-heat-recovery boiler. After cooling the first-stage collectors, the steam is desuperheated and then used to cool the second, higher-temperature stage of TEC collectors. This configuration evolved from the previous, single-TEC-stage configuration shown in figure 1(c), whose performance is limited by the constraint on the collector approach temperature difference ΔT_{coll}. The configuration and parameters of the alternative configuration were chosen to avoid the ΔT_{coll} limit in order to improve system efficiency further. The TEC design parameters for this system were taken from references 11 and 12 and are presented in table II(b).

APPROACH

A number of design parameters such as the exhaust-heat-recovery boiler approach temperature difference ΔT_{ap}, the pinch-point temperature difference ΔT_{pp}, and the ratio of steam flow to compressor-inlet airflow S/A were varied so that the systems could be compared over a range of design values for these parameters. For the STIG/TEC system the ratio of TEC heat absorption rate to fuel input rate based on the fuel higher heating value Q_{TEC}/Q_{fuel} was also varied over a range of possible design values. Parameters for the exhaust-heat-recovery boiler and the TEC-collector cooler are illustrated in figure 2.

In the analysis of the baseline STIG system and the combined cycle the ΔT_{ap} and ΔT_{pp} were varied, and S/A and the system efficiency were calculated. In the combined cycle, assuming a value for the ΔT_{ap} is equivalent to assuming a steam throttle condition for the bottoming cycle. For valid solutions system performance was constrained by thermodynamic and physical limits of system parameters. The S/A was limited by the stoichiometric air-fuel ratio. The exhaust-heat-recovery boiler ΔT_{ap} and ΔT_{pp} and the collector ΔT_{coll} were limited to 10° C (50° F). The stack-gas temperature was limited to the water dewpoint of the stack gas. Performance of the steam bottoming cycle was calculated by using a computer code for steam turbine cycle analysis (refs. 13 and 14). The pressure drop in the water-steam line of the two baseline systems was assumed to be 12 percent.

In analysis of the STIG/TEC system shown in figure 1(c), the ΔT_{pp} was held at a constant value of 10° C (50° F). The Q_{TEC}/Q_{fuel} and S/A were varied so that system efficiency and specific power were calculated over a range of these parameters. The pressure drop in the water-steam line was assumed to be 12 percent. For valid solutions those constraints imposed on the parameters of the baseline systems were also imposed on those of the STIG/TEC system. In addition, Q_{TEC}/Q_{fuel} was constrained between

$$\frac{Q_{TEC}}{Q_{fuel}} = 0 \text{ (no TEC lining on combustor walls)}$$

and

$$\frac{Q_{TEC}}{Q_{fuel}} = \frac{\text{Flame temperature - TEC emitter temperature}}{\text{Flame temperature - Ambient temperature}}$$

In calculating the performance of the alternative configuration of the STIG/TEC system shown in figure 1(d), the Q_{TEC}/Q_{fuel} and S/A were also varied. The same constraints described above were applied to this system. The limit on ΔT_{coll} was avoided by holding the steam from the exhaust-heat-recovery boiler to saturated vapor and desuperheating the steam from the first-stage collector cooler. Pressure drops in the water-steam line were assumed as follow:

(1) 10 Percent drop in the exhaust-heat-recovery boiler
(2) 10 Percent drop in the first-stage collector cooler
(3) 10 Percent drop in the second-stage collector cooler

RESULTS

Figure 3 shows performance results for the baseline STIG system. Figure 3(a) shows the efficiency of the STIG system for a range of boiler design-point parameters including ΔT_{ap}, ΔT_{pp}, and S/A. For a given steam flow rate, an exhaust-heat-recovery boiler could be designed to achieve any number of combinations of ΔT_{ap} and ΔT_{pp}. As the steam flow rate is increased relative to compressor airflow, the amount of heat recovered from the gas turbine exhaust is increased. Furthermore, for a constant turbine-inlet temperature and constant compressor airflow, an increase in steam injected into the combustor requires an increase in fuel input rate.

Along a line of constant ΔT_{ap}, the increase in exhaust-heat recovery with higher steam flow more than compensates for the increase in fuel required to maintain constant turbine-inlet temperature, resulting in higher cycle efficiency. Along a line of constant ΔT_{ap} the larger amount of heat recovery from the exhaust gas results in a lower value of ΔT_{pp}. In contrast, along a line of constant ΔT_{pp}, an increase in steam flow results in an increase in ΔT_{ap} (which results in a decrease in the temperature of the steam injected into the combustor) and lower cycle efficiency. This behavior has been shown for single values of ΔT_{ap} and ΔT_{pp} in reference 1.

A value of 10° C (50° F) for ΔT_{ap} and ΔT_{pp} corresponds to an S/A of 0.158 for this particular STIG system, which results in a cycle efficiency of about 39.1 percent (about a 30 percent increase over that of the simple-cycle gas turbine). The discontinuity in the curves at an S/A of about 0.25 corresponds to a change in the number of turbine stages and hence a discontinuous change in turbine cooling requirements.

The choice of design values for ΔT_{ap} and ΔT_{pp} were limited by a practical boiler design. There are other limitations on system design that are not shown in figure 3(a) but are important to note. For example, the heat recovery from the turbine exhaust must be limited so that the stack-gas inlet temperature is high enough to avoid condensation of water (or if the fuel contains sulfur, to avoid condensation of sulfuric acid). The cycle efficiency and gas turbine specific power are shown in figure 3(b) with S/A, ΔT_{ap}, and ΔT_{pp} as parameters and with various physical and thermodynamic constraints indicated. As shown, a 149° C (300° F) stack-gas temperature is reached very near the design point of $\Delta T_{ap} = \Delta T_{pp} = 10^\circ$ C (50° F). For this particular case, the water dewpoint is lower than 300° F and is shown at higher values of steam flow. The increase in specific power for an increase in S/A is an incentive to consider higher design values of steam injection flow rate. As discussed previously, an increase in steam injection flow to the combustor relative to airflow requires an increase in fuel input. The ultimate limit of steam injection is when the stoichiometric air-fuel ratio is reached. This is shown in the figure at an S/A just above 0.50. Still another possible limit on the S/A is the point where the steam produced in the exhaust-heat-recovery boiler is saturated. It might be desirable to maintain a minimum degree of superheat in the injected steam. For the gas turbine temperature and pressure used in this particular case, this occurs at a ΔT_{ap} greater than 260° C (500° F). As shown in the figure, this limit is met before the dewpoint or stoichiometric limits are reached. For other gas turbine conditions the limits shown in the figure would be expected to shift relative to each other. However, it was indicated in reference 1 that the minimum stack-gas-temperature limit and the saturated-steam limit are reached at lower design steam flows than the stoichiometric limit over a wide range of gas turbine design-point temperatures and pressures.

Figure 4 shows performance results for the conventional combined cycle, which was the other baseline system. In the case of a conventional combined cycle the choice of ΔT_{pp} and ΔT_{ap} design values affects not only the boiler but also the steam turbine bottoming cycle. Consequently a more narrow range of these values is usually considered than was considered for the STIG system. But, to explore the analogies between the cycles, a wide range was nevertheless considered for the combined cycle.

As in the case of the STIG system, an increase in the design steam flow corresponds to an increase in the amount of heat recovered from the exhaust gas. Along a line of constant ΔT_{ap} the steam turbine throttle temperature is constant and hence the steam bottoming cycle efficiency is constant. An increase in design steam flow and hence an increase in heat input to the bottoming cycle results in a higher combined-cycle efficiency. As in the case of the STIG system, an increase in steam flow along a line of constant ΔT_{pp} results in an increase in ΔT_{ap}. For a combined cycle this corresponds to a decrease in steam turbine throttle temperature and a likely decrease in bottoming cycle efficiency. And, as in the case of the steam-injected cycle, despite the increased heat recovery from the gas turbine exhaust, a higher value of design steam flow along a line of constant ΔT_{pp} results in lower overall efficiency. For a design-point value of 10° C (50° F) for both ΔT_{ap} and ΔT_{pp}, the combined-cycle efficiency is 41.3 percent (fig. 4). This is 2.2 percentage points higher than the 39.1 percent calculated for the STIG system.

Figure 5 shows performance results for the STIG/TEC system shown in figure 1(c), the single-stage TEC case. For this system the ΔT_{pp} was held at 10° C (50° F) and the ΔT_{ap} was varied. Figure 5(a) shows efficiency for a range of S/A and Q_{TEC}/Q_{fuel}. The line for a Q_{TEC}/Q_{fuel} of 0 (i.e., no TEC lining) corresponds to the line of the STIG system for a ΔT_{pp} of 10° C. Along this line the specific power increases with increasing steam injection rate relative to the compressor-inlet air (i.e., increasing S/A), but system efficiency drops because of decreasing steam superheat temperature for higher S/A.

As TEC heat absorption is increased by adding more emitter surfaces to the combustor walls (i.e., increasing Q_{TEC}/Q_{fuel}), the system efficiency improves from increased electric generation by the TEC's and the higher temperature of the injected steam from cooling the greater TEC collector area. Lines of constant steam superheat are also shown in figure 5(a). The efficiency of this system is limited by the collector approach temperature difference ΔT_{coll} shown in figure 2. A limit of 10° C was assumed in this study. For the parameter range shown, no other system constraints are reached.

Figure 5(b) shows system efficiency as a function of specific power for the same system. The figure shows that the use of the TEC-lined combustor improves both system efficiency and specific power over those of the STIG system for the same values of S/A. Most significantly, the STIG/TEC system can achieve its highest efficiency at the highest specific power. As compared with the combined cycle, the highest efficiency of the STIG/TEC system is about 1.5 to 1.9 percentage points lower. But because the STIG/TEC system achieves its highest efficiency at significantly higher S/A, the result is substantially higher specific power.

Figure 6 shows performance results of the STIG/TEC combustor system for the alternative configuration shown in figure 1(d). Note that the previous STIG/TEC system has its performance limited by the 10° C constraint imposed on ΔT_{coll}. As was previously discussed, the alternative configuration has two TEC stages and a desuperheater between them to avoid this constraint.

Figure 6(a) shows efficiency as a function of S/A and Q_{TEC}/Q_{fuel}. For a constant Q_{TEC}/Q_{fuel} and injected steam superheated to 316° C (600° F), system efficiency increases as S/A is raised because of a reduction in stack loss associated with a reduction in stack temperature and because of an increased mass flow through the gas turbine. The system efficiency is limited by reaching the ΔT_{pp} limit of 10° C. As the design Q_{TEC}/Q_{fuel} increases from 0.18 to 0.22 and 0.24 for the same 316° C of superheat, more steam can be injected before the ΔT_{pp} limit is reached. System efficiency can be further improved by increasing the superheat and Q_{TEC}/Q_{fuel}. To illustrate this, a single performance point is shown in figure 6(a) for 399° C (750° F) superheat and a Q_{TEC}/Q_{fuel} of 0.28. The efficiency for this case is higher than the maximum efficiencies of the three systems previously discussed.

Figure 6(b) shows both the efficiency and specific power of the alternative STIG/TEC system. For a constant Q_{TEC}/Q_{fuel} and a constant injected-steam superheat, both specific power and efficiency increase as S/A increases.

Figure 6(c) shows the effect of steam superheat on system efficiency for a Q_{TEC}/Q_{fuel} of 0.18. For a constant S/A, if corresponding steam can be injected without reaching the ΔT_{pp} limit of 10° C, higher superheat will result in higher efficiency. Reduction in stack loss is the primary reason for the higher efficiency.

It should be noted that the performance assumed for the TEC's is better for the double-TEC-stage system than for the single-TEC-stage system. Therefore performance improvements from figure 5 to figure 6 cannot be attributed to the configuration change only. The separate contributions of individual factors were identified for a selected design condition as shown in table III. To identify the contribution of the configuration change, performance of the double-TEC-stage system was calculated by using the same generation TEC's that were assumed for the single-TEC-stage system. The effects of the TEC performance advancement are identified by assuming the more advanced TEC's given in reference 12 for the double-TEC-stage system. About 65 percent of the 2.3-percentage-point increase in efficiency from 39.1 percent to 41.4 percent is attributable to the configuration change. About 35 percent is attributable to the improvement in the TEC performance.

CONCLUDING REMARKS

The STIG/TEC system, which combines the advantages of steam injection of gas turbines with conversion of high-temperature combustion heat by thermionic energy converters (TEC), simultaneously improves the efficiency and specific power of the baseline steam-injected gas turbine (STIG) system. The baseline STIG system achieves its peak efficiency at a steam-air ratio (S/A) corresponding to a given design value of boiler pinch-point temperature difference ΔT_{pp}. But the efficiency of this baseline system starts to decline as additional steam is injected because of the drop in steam conditions in the exhaust-heat-recovery boiler. In the STIG/TEC system, however, additional steam injection above the S/A corresponding to an initial maximum efficiency does not reduce the efficiency. It results in higher specific power while achieving the same maximum efficiency. The STIG/TEC system using a single TEC stage, however, reaches its efficiency limit by reaching the constraint imposed on the approach temperature difference of the collector cooler ΔT_{coll}. In an effort to improve the efficiency of the STIG/TEC system by avoiding the ΔT_{coll} limit, an alternative configuration was considered. This alternative system using two TEC stages in lining the combustor walls shows higher efficiency than the configuration using one TEC stage. It should be pointed out that slightly more advanced TEC performance was assumed for the alternative case. Therefore all of the performance improvement cannot be credited to the configuration improvement alone. For a design condition examined, the contribution of the configuration change is larger (about 65 percent of the total efficiency increase) than that of the TEC performance change.

The baseline conventional combined cycle has higher efficiency than does the STIG/TEC system using one TEC stage. However, the specific power of the STIG/TEC system is substantially higher than that of the combined cycle. In addition, the STIG/TEC system using two TEC stages can achieve higher efficiency than the combined cycle.

In this parametric performance analysis, limited consideration was given to variations in the STIG/TEC system configuration. A single case for the two-TEC-stage system using a higher steam superheat and a higher ratio of TEC heat absorption rate to fuel input rate Q_{TEC}/Q_{fuel} indicates a potential for higher efficiency. But identification of a best-system configuration would require analysis of TEC-lined combustor designs and consideration of system capital costs, both of which are beyond the scope of this analysis.

REFERENCES

1. Boyle, Robert J.: Effect of Steam Addition on Cycle Performance of Simple and Recuperated Gas Turbines. NASA TP-1440, 1979.

2. Day, W. H.; and Kydd, P. H.: Maximum Steam Injection in Gas Turbines. ASME Paper 72-JPG-GT-1, Oct. 1972.

3. General Electric Company: Steam Injected Gas Turbine Study: An Economic and Thermodynamic Appraisal. EPRI AF-1186, Electric Power Research Institute, 1979.

4. Fraize, W. E.; and Kinney, C.: Effects of Steam Injection on the Performance of Gas Turbine Power Cycles. J. Eng. Power, vol. 101, no. 2, April 1979, pp. 217-227.

5. Stochl, Robert J.: Off-Design Analysis of a Gas Turbine Powerplant Augmented by Steam Injection Using Various Fuels. NASA TM-81611, 1980.

6. Stochl, Robert J.: Assessment of Steam-Injected Gas Turbine Systems and Their Potential Application. NASA TM-82735, 1982.

7. Miskolczy, G.; et al.: Thermionic Combustor Application to Combined Gas and Steam Turbine Power Plants. Proceedings of 16th Intersociety Energy Conversion Engineering Conference, Vol. 2, ASME, 1981, pp. 1956-1961.

8. Fitzpatrick, G. O.; et al.: Thermionic Converters for Increased Performance in Gas Turbine Power Plants. Proceedings of 16th Intersociety Energy Conversion Engineering Conference, Vol. 2, ASME, 1981, pp. 1962-1967.

9. Muhlhauser, H.; and Eckert, W.: Steam Turbine in Power Stations for Peak and Medium Load. Combustion, vol. 48, no. 9, Mar. 1977, pp. 11-23.

10. Huffman, F. N.; and Miskolczy, G.: Thermionic Energy Conversion Topping System. ASME Paper 77-WA/ENER-6, Nov. 1977.

11. Morris, J. F.: Comments on TEC Trends. International Conference on Plasma Science, Conference Record-Abstracts, Institute of Electrical and Electronics Engineers, Montreal, Canada, Abstract 6D10, 1979, p. 166. (Also NASA TM-79317, 1979.)

12. Morris, J. F.: Potentialities of TEC Topping - A Simplified View of Parametric Effects. NASA TM-81468, 1980.

13. Fuller, L. C.: and Stovall, T. K.: User's Manual for PRESTO: A Computer Code for the Performance of Regenerative, Superheated Steam Turbine Cycles. (ORNL-5547, Oak Ridge National Lab.; NASA Order C-10669-D.) NASA CR-159540, 1979.

14. Choo, Yung K.; and Staiger, Peter J.: New Features and Applications of PRESTO: A Computer Code for the Performance of Regenerative, Superheated Steam Turbine Cycles. NASA TP-1954, 1982.

TABLE I. - GAS TURBINE PARAMETERS

Turbine-inlet temperature, °C (°F)	1093 (2000)
Compressor pressure ratio	16
Compressor polytropic efficiency, percent	87
Turbine polytropic efficiency, percent	87
Turbine mechanical efficiency, percent	98
Generator efficiency, percent	98
Combustor efficiency, percent	99
Ambient air condition:	
Temperature, °C (°F)	15 (59)
Pressure, MPa (psia)	0.101 (14.7)
Relative humidity, percent	60
Combustor pressure drop, percent	4
Gas-side pressure drop in exhaust-heat-recovery boiler, percent	4
Water-inlet temperature, °C (°F)	15 (59)
Pump efficiency, percent	70
Steam-side pressure drop	Varies by system (see text)
Fuel	Light distillate
High heating value, MJ/kg (Btu/lb)	43.2 (18 600)

TABLE II. - THERMIONIC ENERGY CONVERTER PARAMETERS

(a) STIG/TEC[a] system (fig. 1(c))

Emitter temperature, K (°F)	1600 (2420)
Collector temperature, K (°F)	950 (1250)
TEC efficiency, percent	20
Inverter efficiency, percent	95

(b) Alternative STIG/TEC[a] system (fig. 1(d))

First-stage TEC:	
Emitter temperature, K (°F)	1600 (2420)
Collector temperature, K (°F)	850 (1070)
TEC efficiency, percent	29
Inverter efficiency, percent	95
Second-stage TEC:	
Emitter temperature, K (°F)	1800 (2780)
Collector temperature, K (°F)	925 (1206)
TEC efficiency, percent	30.2
Inverter efficiency, percent	95

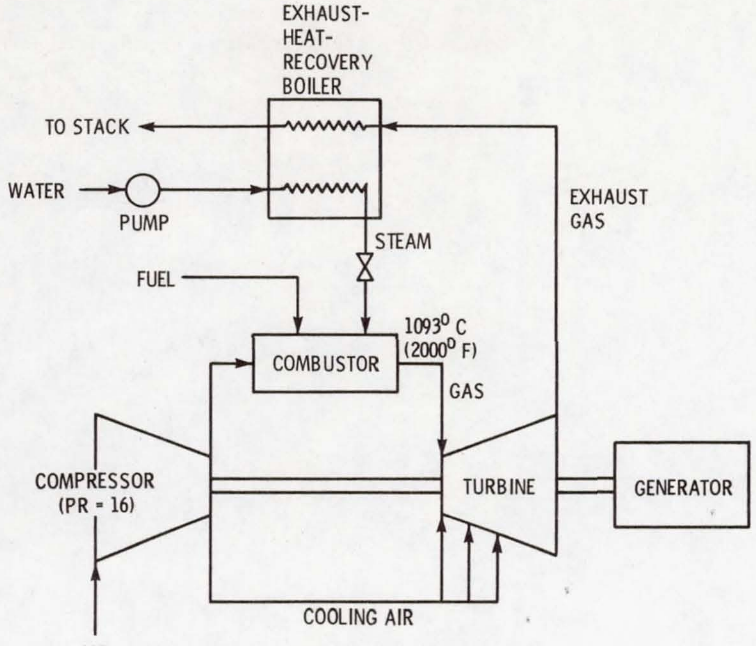
[a] Steam-injected gas turbine/thermionic energy converter system.

TABLE III. - CONTRIBUTIONS OF CONFIGURATION CHANGE AND THERMIONIC ENERGY CONVERTER ADVANCEMENT TO SYSTEM PERFORMANCE

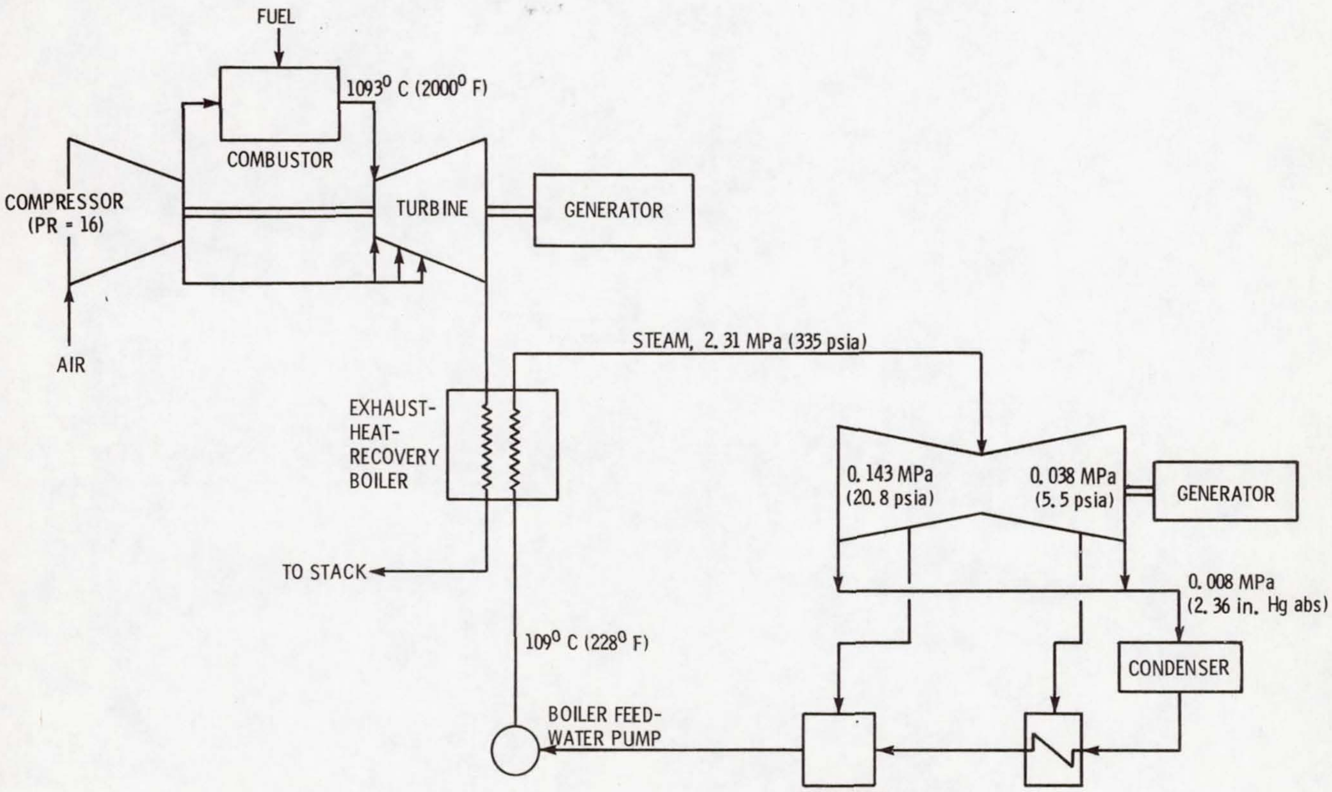
	Single-stage system	Two-stage system	Two-stage system
Degree of TEC advancement	Base	Same as base	More advanced
Source of TEC performance data	Ref. 10	Ref. 10	Ref. 12
System configuration	Fig. 1(c)	Fig. 1(d)	Fig. 1(d)
Design parameters:			
Steam-air ratio	0.34	0.34	0.34
Ratio of TEC heat absorption to fuel input rate	0.28	0.28	0.28
Superheat, °C (°F)	[a]427 (800)	400 (752)	400 (752)
First stage			
Emitter temperature, K (°F)	1600 (2420)	1600 (2420)	1600 (2420)
Collector temperature, K (°F)	950 (1250)	850 (1070)	850 (1070)
TEC efficiency, percent	20	26	29
Second stage			
Emitter temperature, K (°F)	(b)	1800 (2780)	1800 (2780)
Collector temperature, K (°F)	(b)	925 (1206)	925 (1206)
TEC efficiency, percent	(b)	27	30.2
Performance:			
Efficiency, percent	39.1	40.6	41.4
Specific power, W-hr/kg	203	212	216

[a] In the single-TEC-stage system, the superheat is dependent on the steam-air ratio.

[b] Not applicable.

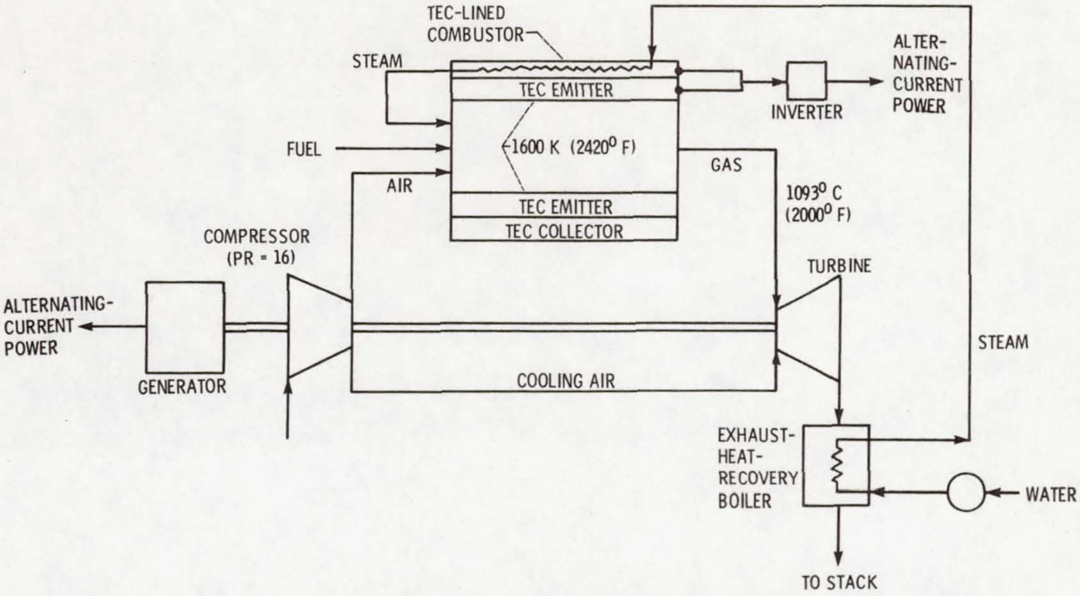


(a) Steam-injected gas turbine (STIG).

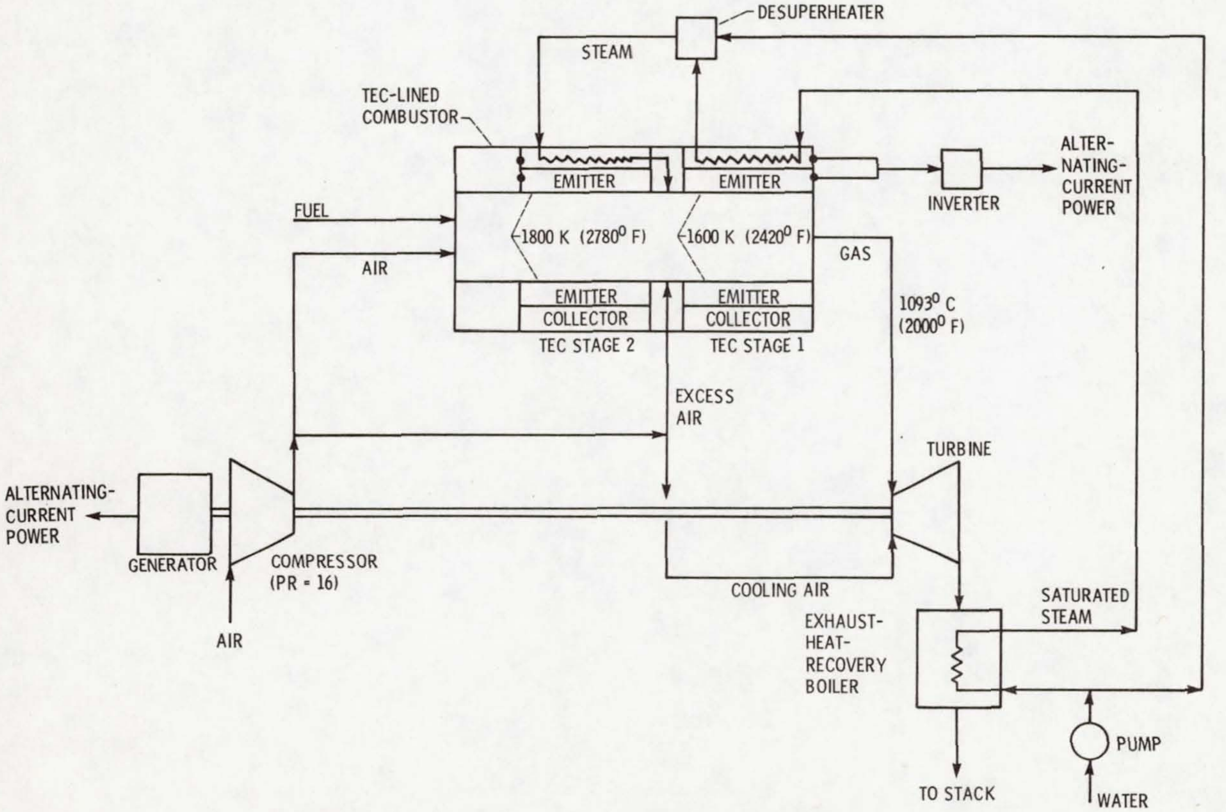


(b) Combined gas turbine/steam turbine cycle.

Figure 1. - System configurations.



(c) Steam-injected gas turbine with a TEC-lined combustor (STIG/TEC combustor).



(d) An alternative configuration of steam-injected gas turbine with a TEC-lined combustor.

Figure 1. - Concluded.

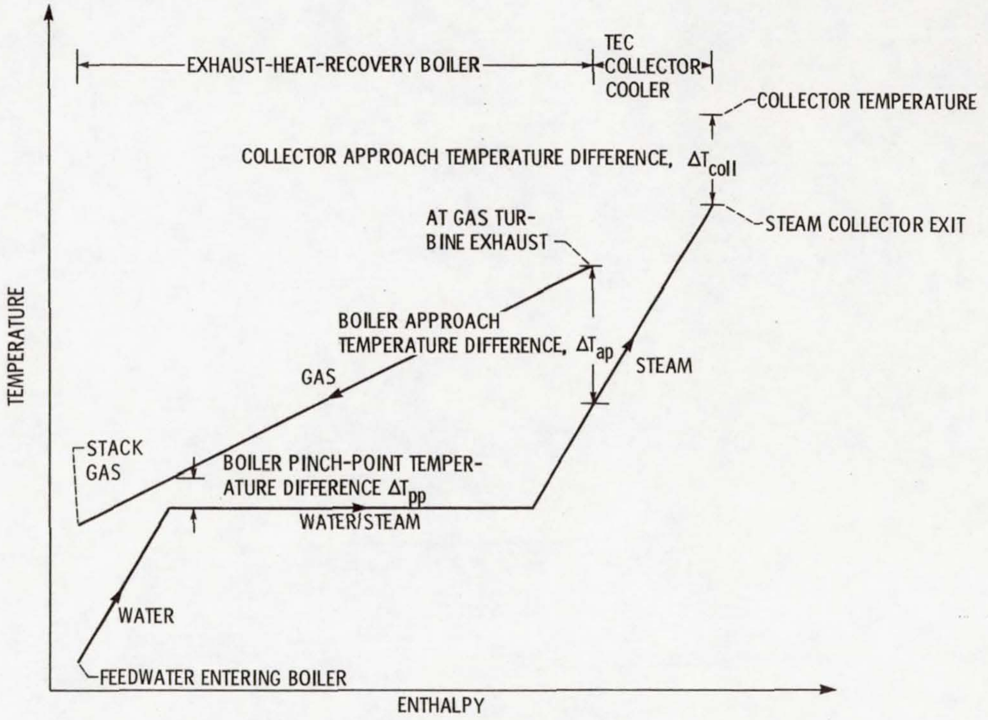
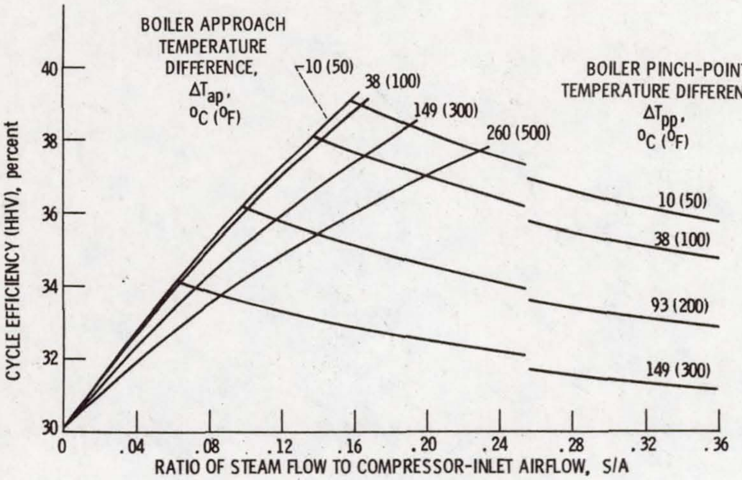
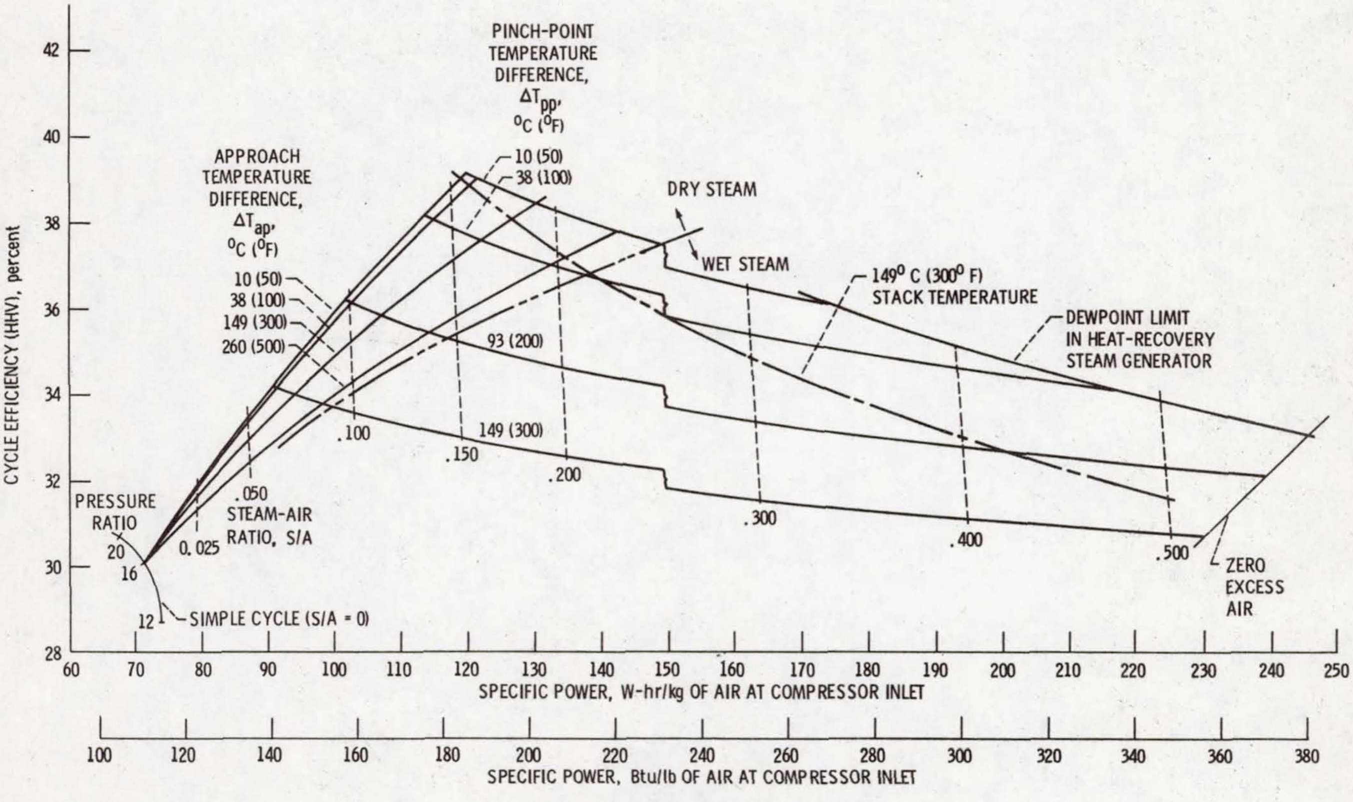


Figure 2. - Illustration of heat exchanger parameters for the STIG/TEC system in figure 1 (c).



(a) Efficiency as a function of steam-air ratio.



(b) Efficiency as a function of specific power.

Figure 3. - Performance of steam-injected gas turbine (STIG).

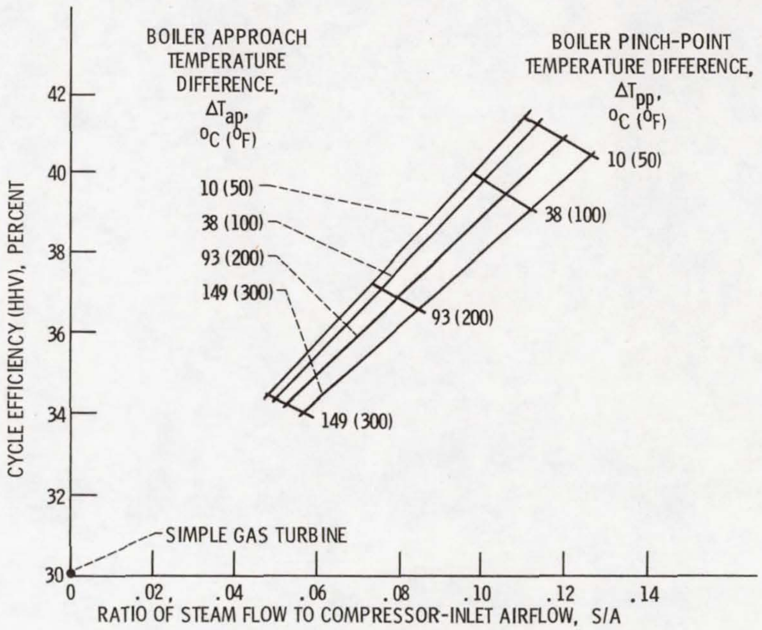
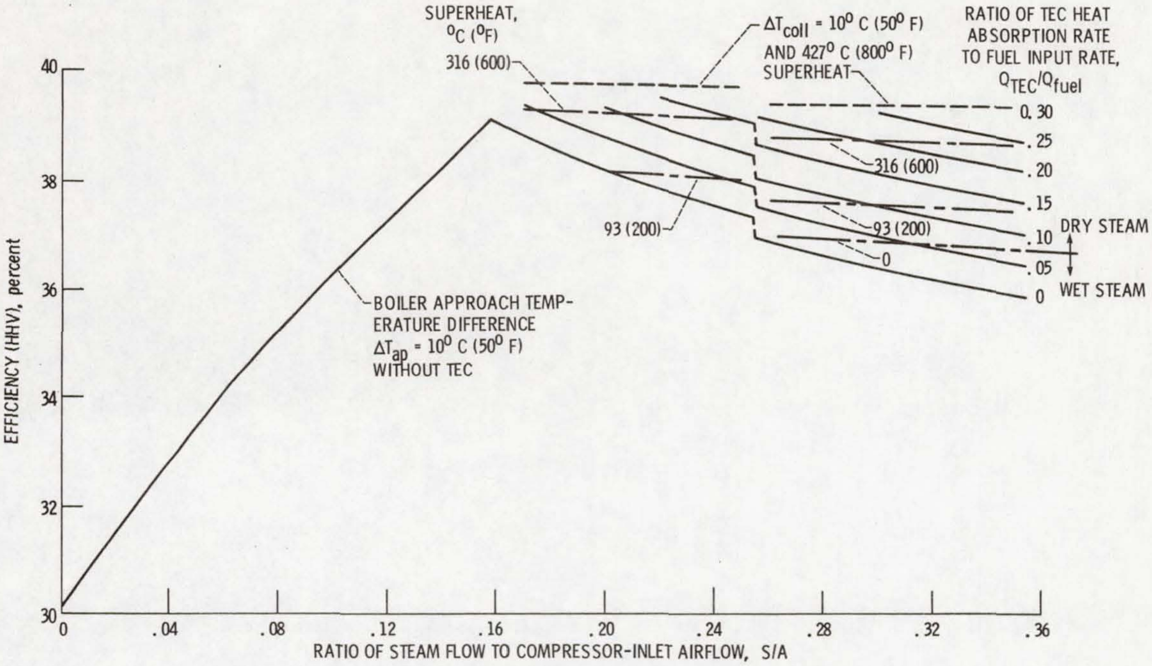
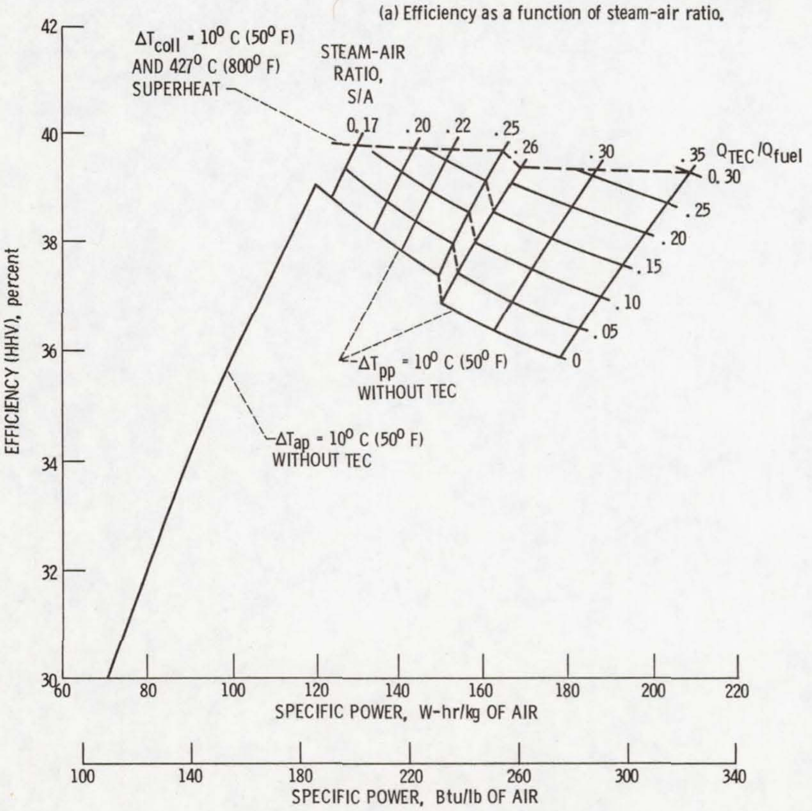


Figure 4. - Performance of combined gas turbine/steam turbine cycle.

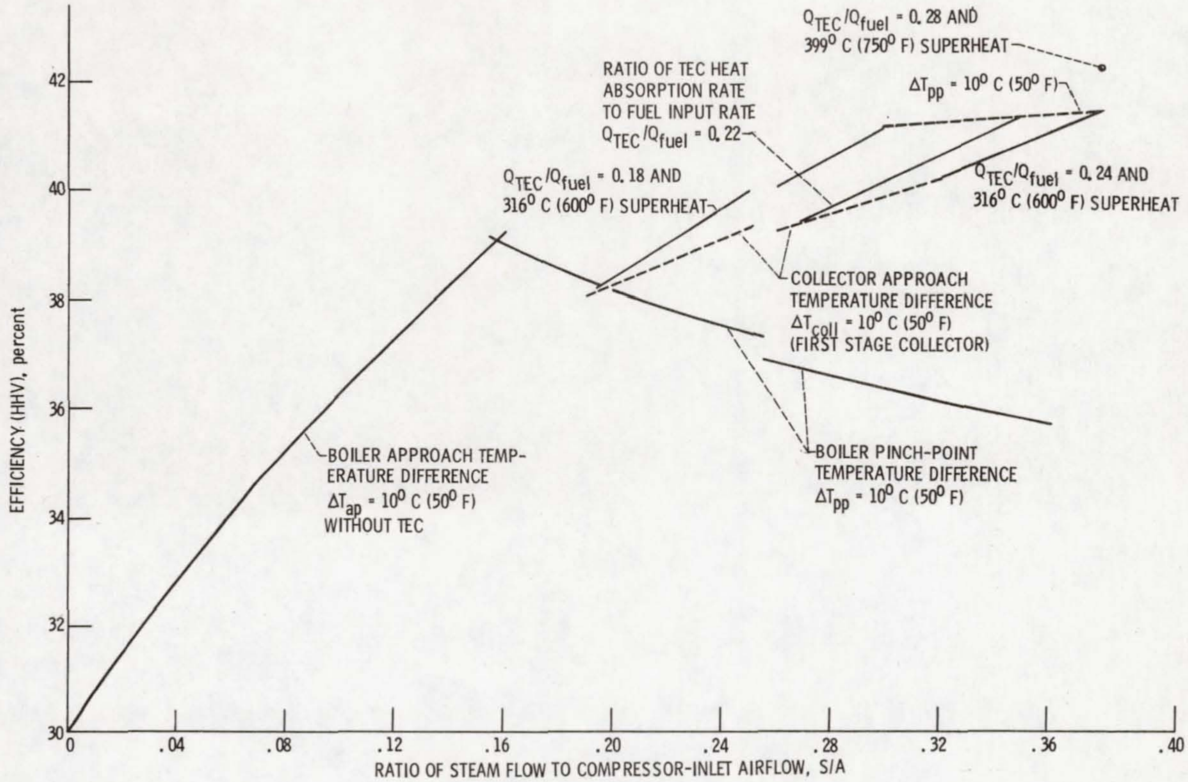


(a) Efficiency as a function of steam-air ratio.

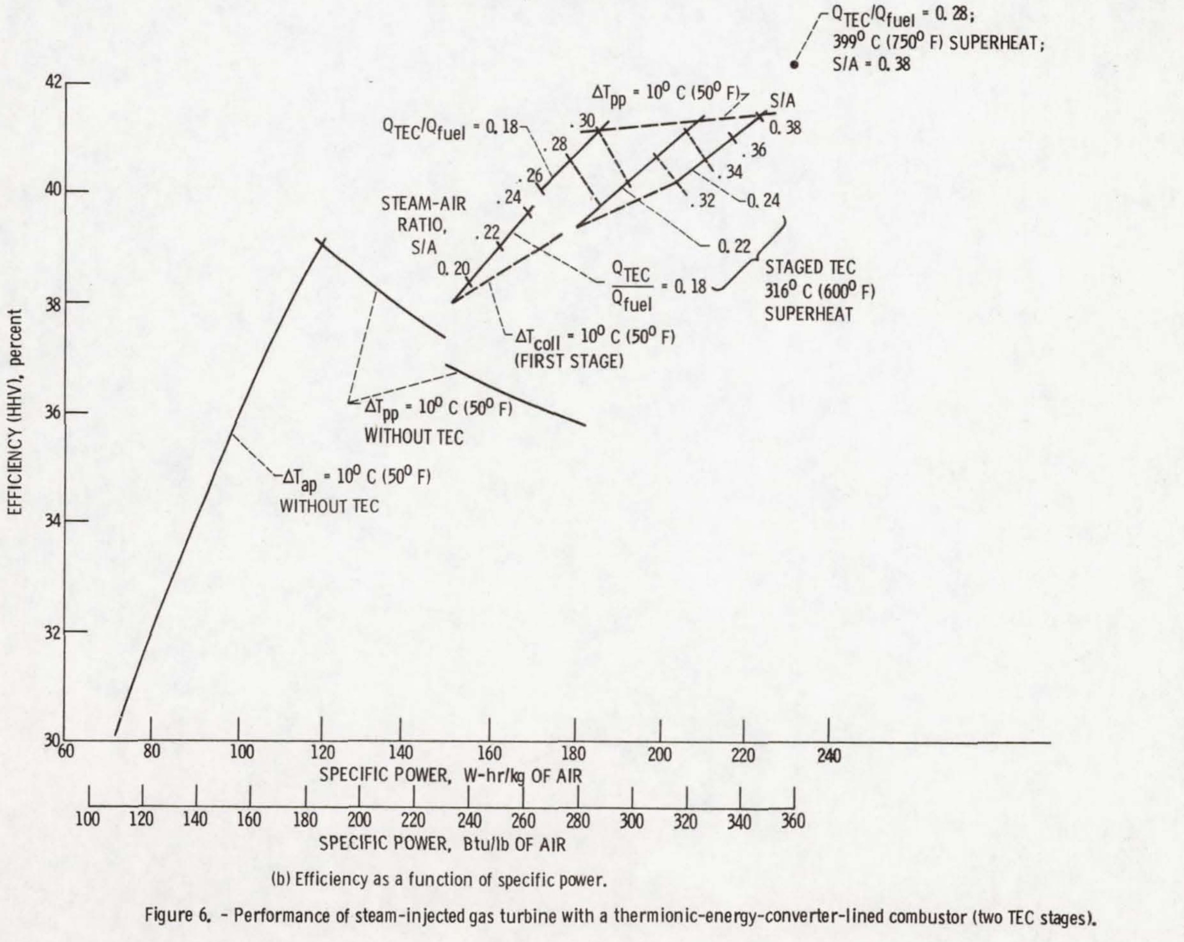


(b) Efficiency as a function of specific power.

Figure 5. - Performance of steam-injected gas turbine with a thermonic-energy-converter-lined combustor (one TEC stage).

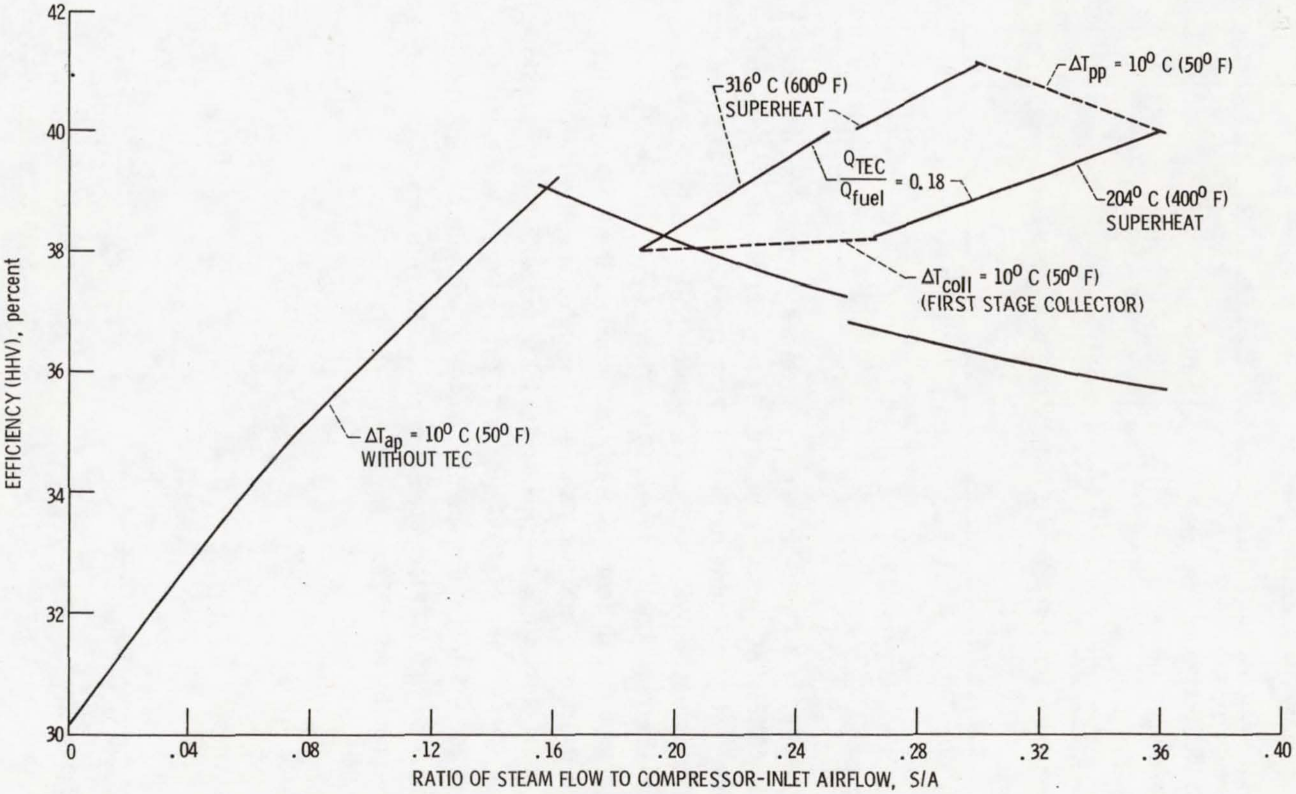


(a) Efficiency as a function of steam-air ratio.



(b) Efficiency as a function of specific power.

Figure 6. - Performance of steam-injected gas turbine with a thermionic-energy-converter-lined combustor (two TEC stages).



(c) Effect of superheat.

Figure 6. - Concluded.

1. Report No. NASA TM-82736	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle PARAMETRIC PERFORMANCE ANALYSIS OF STEAM-INJECTED GAS TURBINE WITH A THERMIONIC-ENERGY-CONVERTER-LINED COMBUSTOR	5. Report Date February 1982 6. Performing Organization Code 778-46-12
7. Author(s) Yung K. Choo and Raymond K. Burns	8. Performing Organization Report No. E-1048 10. Work Unit No.
9. Performing Organization Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135	11. Contract or Grant No. 13. Type of Report and Period Covered Technical Memorandum
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546	14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

The performance of steam-injected gas turbines having combustors lined with thermionic energy converters (STIG/TEC systems) was analyzed and compared with that of two baseline systems: a steam-injected gas turbine (without a TEC-lined combustor) and a conventional combined gas turbine/steam turbine cycle. Common gas turbine parameters were assumed for all of the systems. Two configurations of the STIG/TEC system were investigated. In both cases, steam produced in an exhaust-heat-recovery boiler cools the TEC collectors. It is then injected into the gas combustion stream and expanded through the gas turbine. The STIG/TEC system combines the advantage of gas turbine steam injection with the conversion of high-temperature combustion heat by TEC's. The addition of TEC's to the baseline steam-injected gas turbine improves both its efficiency and specific power. Depending on system configuration and design parameters, the STIG/TEC system can also achieve higher efficiency and specific power than the baseline combined cycle.

17. Key Words (Suggested by Author(s)) Thermionics Gas turbines Steam injection Combined cycle	18. Distribution Statement Unclassified - unlimited STAR Category 44

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages	22. Price*

National Aeronautics and
Space Administration

Washington, D.C.
20546

Official Business
Penalty for Private Use, $300

SPECIAL FOURTH CLASS MAIL
BOOK

Postage and Fees Paid
National Aeronautics and
Space Administration
NASA-451

U.S. MAIL

NASA

POSTMASTER: If Undeliverable (Section 158
Postal Manual) Do Not Return