DUAL FLUID CYCLE

Integration of the Brayton and Rankine Cycle to Maximize Gas Turbine Performance--a Cogeneration Option

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ABSTRACT

The Brayton and Rankine cycles are well known and widely used in their own way to generate power. A combining of the fluids of the two cycles has been proposed by International Power Technology and tested by Allison Gas Turbine Operations. Steam generated by the exhaust heat is mixed with the fuel and air in the gas turbine combustion chamber prior to expansion through the turbine.

The thermal efficiency of an existing engine can be increased by 40% and power output by 60% at constant turbine temperature. This concept is identified as the Dual Fluid Cycle (DFC).

In addition to the basic improvement in cycle performance, the DFC provides an added degree of flexibility to the power plant engineer in his effort to satisfy plant needs for power, heat, and steam.

Allison test results of this concept on a Model 501-KB engine have been correlated with a computer model of the engine and show good agreement. This paper will show how the DFC can be used to maximize thermal efficiency while meeting the requirement for power and steam in selected cases. Comparisons will be made to other options for power and steam generation.

DISCUSSION

The gas turbine power plant is meeting a wide range of energy requirements the world over. For the most part these turbines are simple Brayton cycle engines and therefore reject a significant amount of heat to the atmosphere. The thermal efficiency of this cycle is in the range of 22% to 30%. Variations to the Brayton cycle such as regeneration or intercooling can improve the performance of the engine; however, they add a degree of complication to the system. In many cases this cannot be justified in terms of the resulting magnitude of improvement.

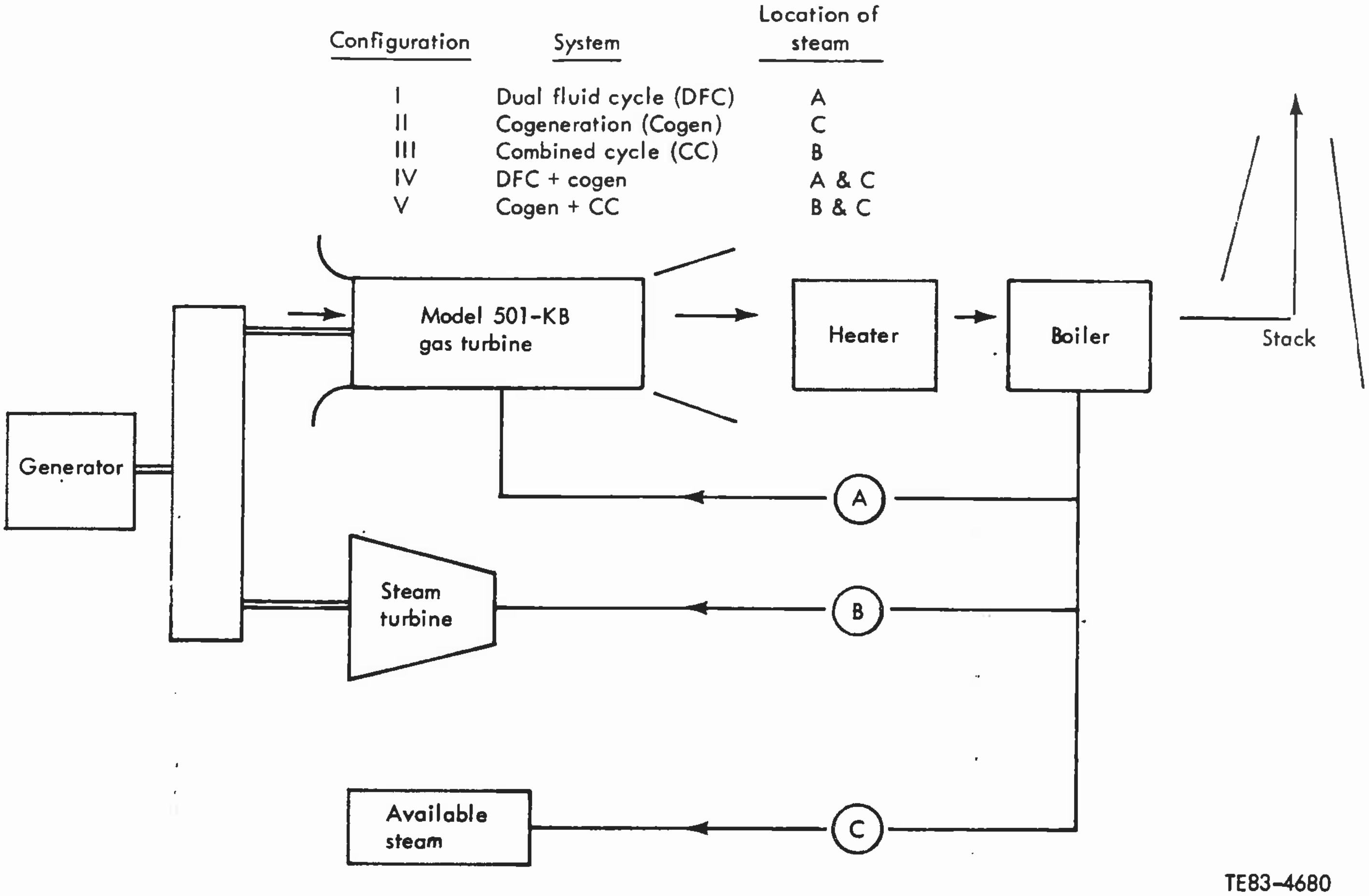
An alternate approach to variations from the Brayton cycle is to combine the Brayton with the Rankine cycle and recover the exhaust energy by the addition of a waste heat boiler. This will provide for the generation of steam or an organic vapor which can be used in various ways to augment the performance of the system. Typical cases would be either a combined cycle or a cogeneration configuration. (As used here, combined cycle refers to power generation only and cogeneration refers to the case in which both power and steam are available from the system.) A better option for using the steam generated by the exhaust heat has been demonstrated.

This means of increasing power and thermal efficiency, which has been proposed by International Power Technology (IPT) and others (Ref 1) and has been tested by Allison Gas Turbine Operations, consists of injecting the steam generated by the waste heat boiler into the gas turbine at the combustor. This concept is identified as the Dual Fluid Cycle (DFC). It incorporates a complete integration of the Brayton and Rankine cycles in that the fluids of both are intimately mixed in the combustor of the turbine. There exists a twofold benefit from this mixing of the air and steam prior to the expansion of the mixture through the turbine. Since the output of the turbine is proportional to the mass flow, the power increases directly with the amount of steam added in the combustor. This accounts for about half the total power increase from the DFC. The other half of the power increase is a result of an increase in the specific heat of the gas mixture, which is expanded through the turbine.

The specific heat of the mixture of air, fuel, and steam of the DFC is 1.293 kJ/kg·°C for a typical case whereby the normal gas composition of the engine would have a specific heat of 1.122 kJ/kg·°C. This is a 15% increase in specific heat.

When considering the DFC along with cogeneration and the combined cycle, the number of options for improving the performance of the gas turbine system are enhanced.

Figure 1 presents a schematic diagram of a gas turbine plant in which the various concepts can be seen. This figure includes the DFC, cogeneration, and combined cycle as well as combinations of these.



Configuration	System	Location of steam
I	Dual fluid cycle (DFC)	A
II	Cogeneration (Cogen)	C
III	Combined cycle (CC)	B
IV	DFC + cogen	A & C
V	Cogen + CC	B & C

Figure 1. Schematic of potential systems.

A heater between the turbine and boiler is included to encompass yet another option and expand the range of performance of the system.

The most cost effective option will be determined by the power and steam required from the system. Once these are defined, effort should be made to evaluate the merits of the various systems to ensure the best selection possible.

This paper will discuss the various options and present the results of calculations for the different systems in terms of power output, thermal efficiency, and available steam. In addition to the primary concerns of power, thermal efficiency, and steam, consideration will be given to the flexibility of the system and the ability to meet peak requirements for either steam or power.

For the purpose of this paper the basic prime mover will be assumed to be the Allison Model 501-KB engine. Use of this engine operating at its continuous rating will allow the examination of how the heater and boiler assumptions will affect the overall plant performance of a DFC, combined cycle, or cogeneration plant built around an existing engine. The Model 501-KB is a constant-speed engine and is particularly well suited to the DFC concept because of its available surge margin and the tolerance of the combustor to large quantities of steam flow. The surge margin of the engine at continuous power is in excess of 35%; thus it can accept large quantities of steam. Experience with both water and steam in the combustor has shown good stability in the burner and a minimum effect on combustion efficiency.

Allison has tested a Model 501-KB engine (Ref 2) incorporating a steam manifold around the burner, as shown in Figure 2. The engine was run over a wide range of turbine inlet temperatures and steam flows. This testing verified the projected DFC performance in that the test results showed a high degree of correlation with the analytical performance estimates. These estimates were based on a simulation that incorporated the thermodynamic characteristics of the steam, fuel, and air mixture. Figures 3 and 4 show this correlation for power and thermal efficiency respectively. As noted in Figure 4, the demonstration testing to evaluate the DFC was done with 205°C steam, which was saturated steam that was available from the power house. This eliminated the requirement to build a boiler for this test but in no way compromised the test results. A boiler on the engine would have provided the ability to generate the same quantity of steam at superheated conditions. While the steam temperature has little effect on power, it does affect the thermal efficiency. At 9000 kg/h steam flow, the change in thermal efficiency would have increased from 27.3% to 39.7% with 482°C compared with 205°C steam.

Based on these test results, the DFC in combination with the Model 501-KB engine provides a viable option to cogeneration or the combined cycle to satisfy a requirement for power and steam. Figure 5

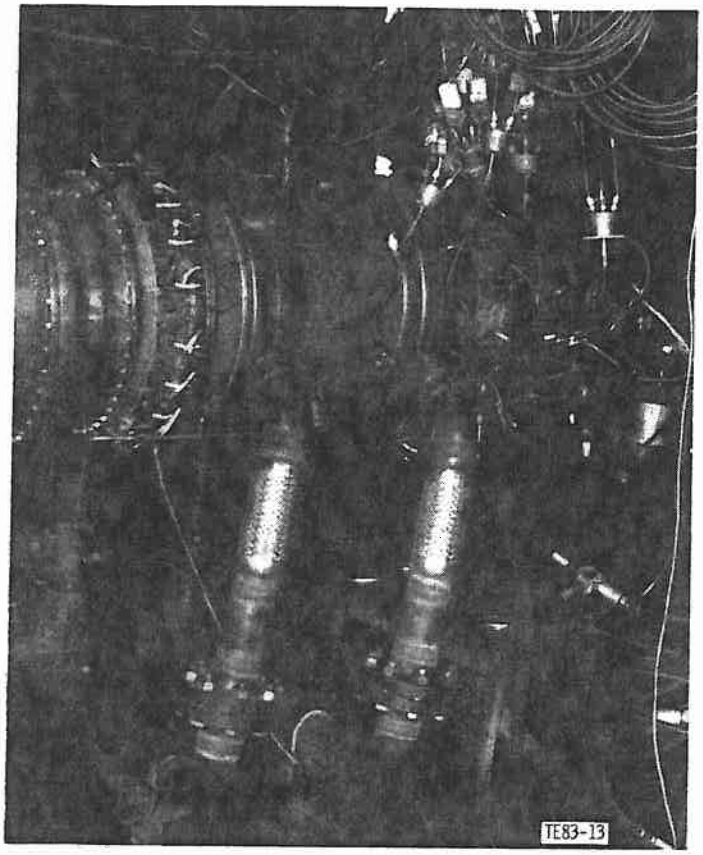


Figure 2. Steam connections to the DFC engine.

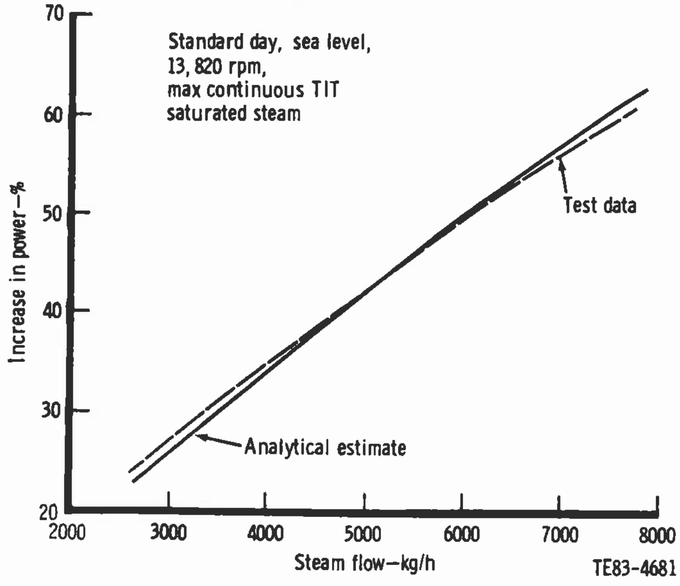


Figure 3. Comparison of test result with analytical estimate for power of Allison Model 501-KB DFC engine.

shows the performance potential of the Model 501-KB DFC system for a matrix of turbine temperatures and steam flows.

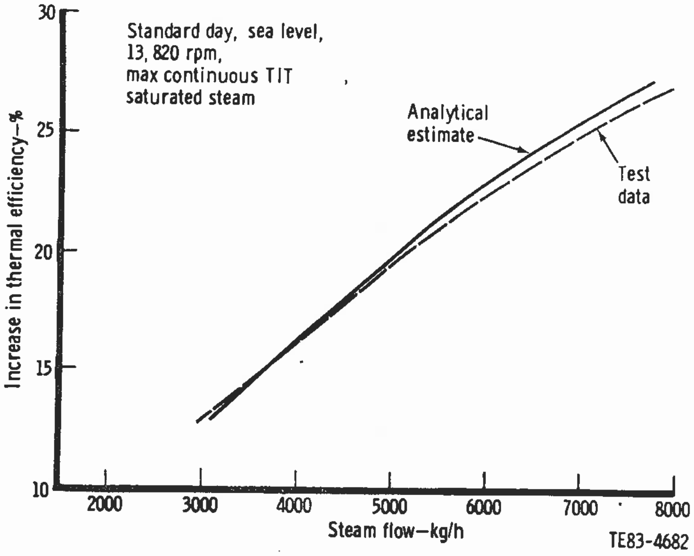


Figure 4. Comparison of test result with analytical estimate for thermal efficiency of Allison Model 501-KB DFC engine.

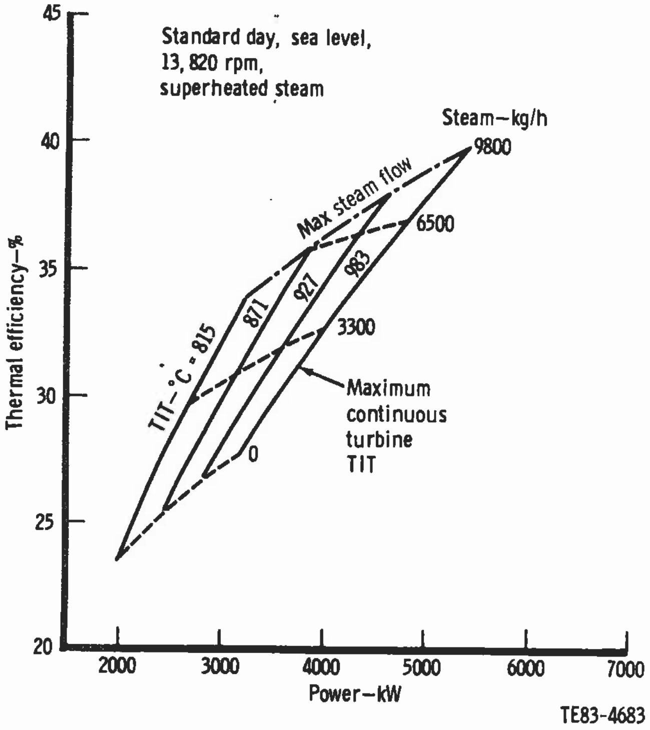


Figure 5. Performance potential of the Model 501-KB DFC system for various turbine temperatures and steam flows.

The other components of the proposed systems are also a known quantity. The heater between the turbine exhaust and boiler consists of a conventional combustor that can supply any desired temperature rise to the exhaust gas. This will in turn provide the ability to increase either the temperature and/or quantity of steam from the boiler. Modulation of the fuel to this burner can be used as a throttle to control the output of the system in terms of either power and/or steam.

The boiler is based on existing technology. The temperature difference between the steam and exhaust gas and the stack temperature are typical of current design practice.

The steam turbine performance is representative of an "off the shelf" level of technology for a noncondensing turbine exhausting to ambient pressure. It should be recognized that the efficiency of this type of turbine in the 2 to 4 MW range will be considerably less than the 90% of the gas turbine.

Table I lists the assumptions and considerations that have been used for the various components of the system. The basic performance for each of the five systems was calculated for the case of no reheat with the Model 501-KB engine operating at its maximum continuous turbine temperature of 983°C. The results of this calculation are shown in Table II.

RESULTS

When operating as a DFC (Configuration I), the boiler can produce up to 9000 kg/h of superheated steam. When this steam is returned to the combustor, the power will increase from 3210 kW to 5400 kW (or by 65%) and the thermal efficiency will go from 28.3% to 39.7% (which is a 40% increase in thermal efficiency). The limits are determined by the maximum amount of steam the boiler can generate. The steam pressure is just high enough to match the combustor pressure. A throttle line can be defined at the continuous turbine temperature by returning less than the maximum steam flow to the cycle. This is shown on Figure 6 for two cases. One is for superheated steam and the other for saturated steam. The saturated steam will produce more power in the engine because the same boiler is able to produce more steam at the lower temperature. There is, however, a thermal efficiency penalty when using saturated rather than superheated steam caused by the requirement for additional fuel to raise the gas mixture to turbine inlet temperature.

Table I.
Assumptions and considerations.

Basic Engine--Model 501-KB

Compressor pressure ratio = 9.3
Continuous turbine inlet temp = 983°C
Airflow = 15 kg/s
Output = 3270 kW
Thermal efficiency = 28.3

Boiler

Natural circulation
Economizer for preheat
Separate section superheater
Maximum temp = 760°C
Maximum steam flow = 13000 kg/h
Pinch point Delta T = 28°C

Steam turbine

Noncondensing
Multistage axial
Efficiency = 75%

Reheater

Pressure loss = 3.0%
Efficiency = 95%
Temperature rise max = 316°C

The throttling characteristic of the engine can be seen for two cases. One is operation at constant turbine inlet temperature (TIT) with the steam flow rate changing and the other is at maximum steam flow with TIT changing. It can be seen that the latter produces the best performance. This method of throttling also enhances the engine life because a given power is obtained at reduced TIT.

Configuration II is the cogeneration system, in which all the steam produced is used for purposes other than the generation of power. With this system the steam available is reduced to 7360 kW/h because the steam is not returned to the engine and, thus, there is less flow in the exhaust to generate steam. Figure 7 shows the capability of the engine to generate steam in terms of quantity of steam as a function of pressure and temperature of the steam.

Configuration III of Table II shows the combined cycle performance using the Model 501-KB engine. This performance is based on the expansion of the steam, as generated in Configuration II, through a steam turbine and on combining this power with the output of the engine. The power ouput and thermal efficiency as a function of steam pressure and temperature are shown in Figure 8. The addition of a condenser in this system and the use of a condensing turbine would increase the output from this system. This study is limited, however, to the case of a noncondensing turbine.

In combining the DFC with cogeneration, the power output from the engine can be increased and steam can

Table II.
Performance potential of various systems using Model 501-KB engine.

Conditions: Standard day, sea level, continuous rated temperature, 13,820 rpm, no reheat, basic engine--3200 kW, 27.7% thermal efficiency, steam pressure--1034 kPa, steam temperature--482°C

	Configuration				
	Dual Fluid Cycle (DFC)--I	Cogeneration (Cogen)--II	Combined Cycle (CC)--III	DFC and Cogen--IV	CC and Cogen--V
Steam quantity--kg/h					
Used by engine	9000	0	0	4250	0
Steam turbine	0	0	7360	0	3600
Available	0	7360	0	3760	3760
Output					
Power--kW	5400	3200	4220	4300	3720
Thermal efficiency--%	39.7	27.7	36.6	34.2	31.1

Note: Thermal efficiency is based on heat input and power output only and does not include accounting for steam. A thermal efficiency accountability incorporating the energy in the steam is subject to and will vary with the condition of the steam and boiler assumptions.

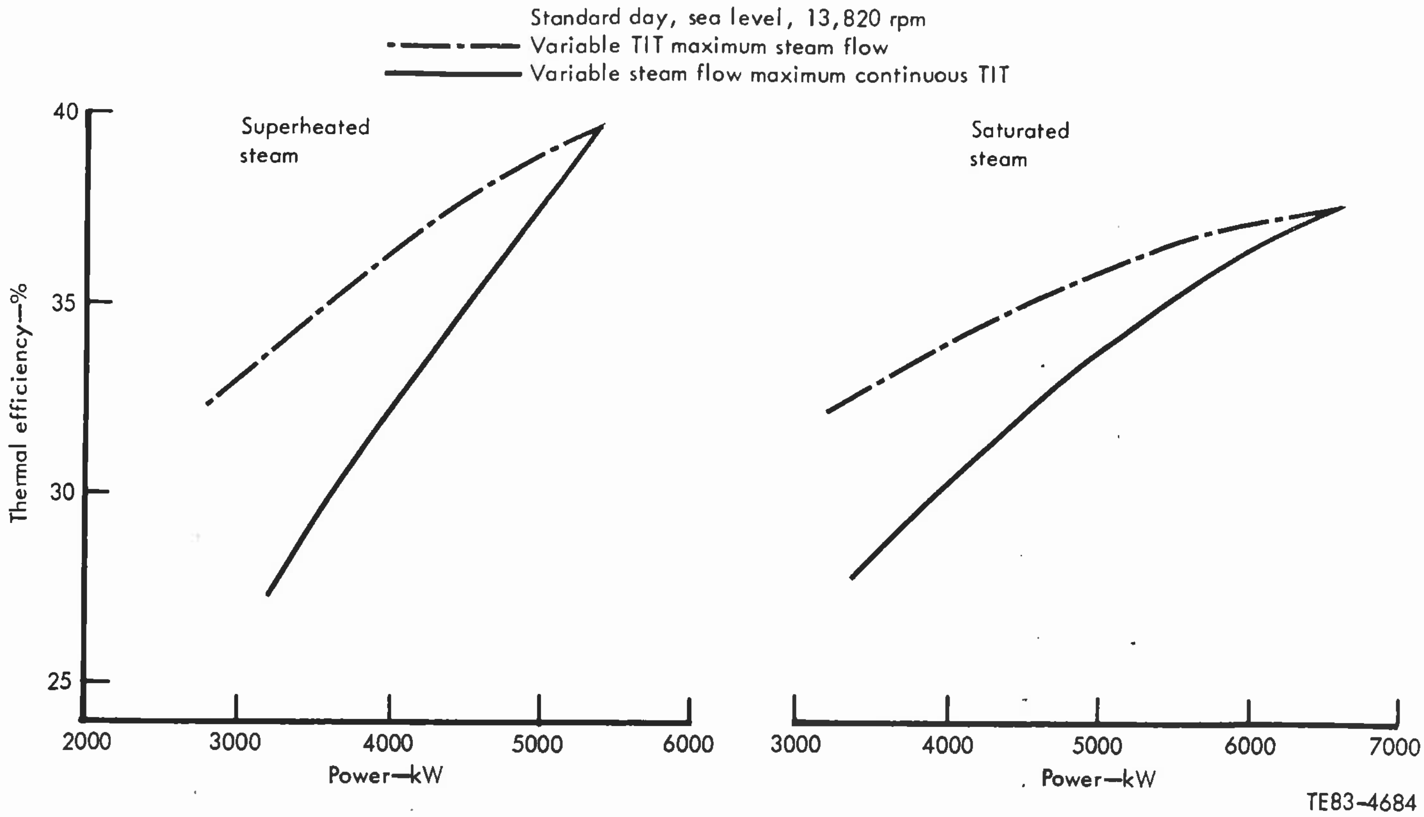


Figure 6. Throttle line for Configuration I of Model 501-KB DFC engine with superheated and saturated steam.

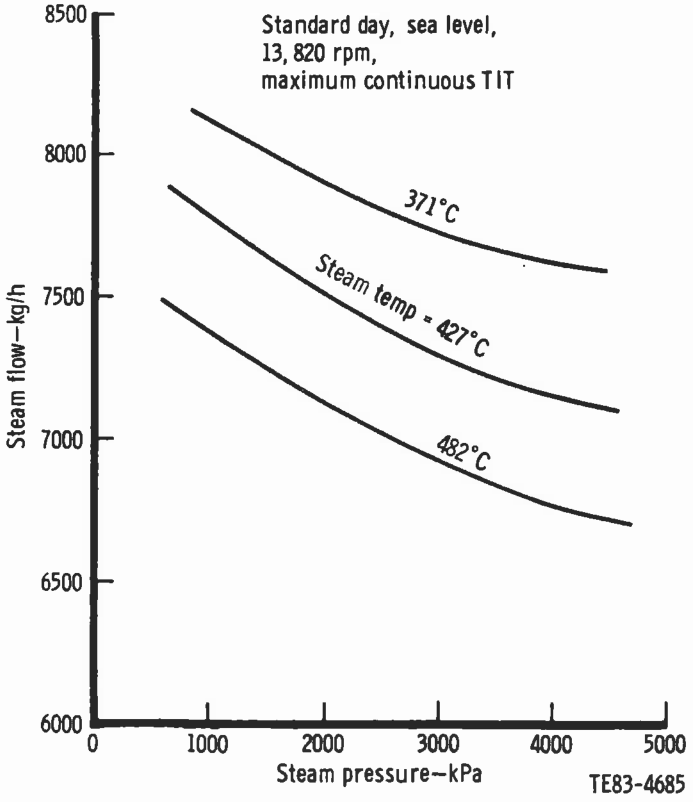


Figure 7. Steam generation capability of Configuration II using Model 501-KB engine.

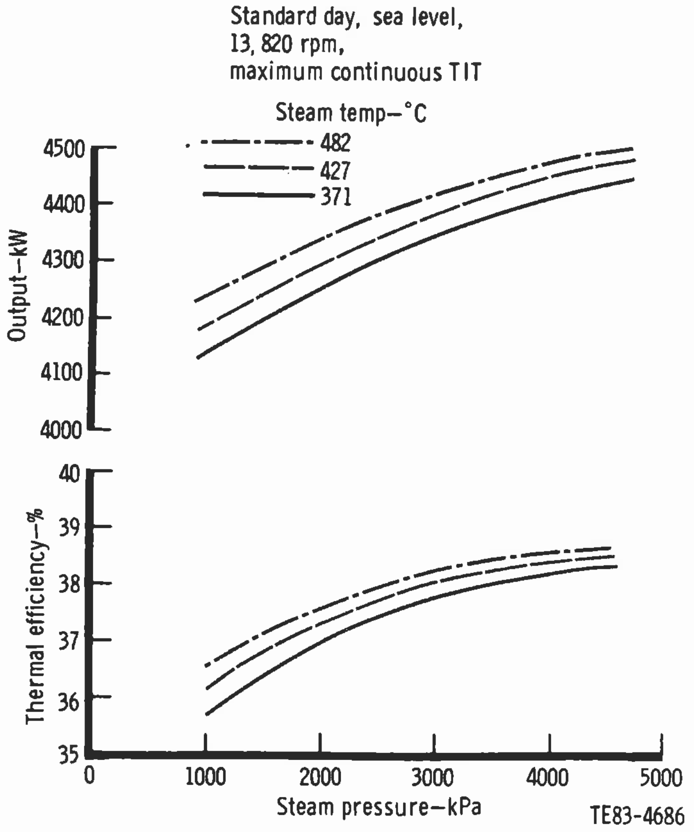


Figure 8. Power output and thermal efficiency of Configuration III using Model 501-KB engine.

be made available for process or other uses. The magnitude of power increase versus the amount of steam generated can be varied to meet any particular requirement within the limits of the system.

Configuration IV in Table II shows a case in which 3760 kg/h of steam is available from the system. This results in 4300 kW being provided by the engine. Figure 9 shows the range of performance in terms of available steam flow and power for the engine operating at its continuous rated temperature.

The last configuration, Configuration V on Table II, shows the performance of a system in which the combined cycle and cogeneration are evaluated. The performance is shown for a case in which the available steam flow is the same as the DFC system with cogeneration. It can be seen that, for the same steam flow, the power and thermal efficiency are both lower than the system incorporating the DFC.

Table III shows the effect of adding the reheat burner between the turbine exhaust and the boiler. As might be expected, this is a means to increase the output of the system at the expense of thermal efficiency. The increased output of the system in terms of either power or steam rate would be available to meet peak output requirements.

As previously mentioned, the most cost-effective system to meet a requirement for power and steam will be determined by the specific requirement. It is evident from the data presented here, however, that DFC can offer advantages to the system that cogeneration and/ or the combined cycle do not have. The ability to increase the power output of the engine by 60% and thermal efficiency by 40% at the same turbine temperature (with only the addition of a steam manifold around the engine equipped with a waste heat boiler) is a highly desirable option.

In addition to the increase in power and thermal efficiency, the DFC concept also provides a high degree of flexibility. If there is a requirement for process steam that is less than the capability of the boiler, the excess can be supplied to the engine, thus increasing the overall efficiency of the system. On the other hand, if steam is being generated by some means other than the engine exhaust, the steam can be supplied to the engine to provide increased power output at a high level of efficiency. The ability to increase power and thermal efficiency and throttle the Model 501-KB engine efficiently with a minimum modification to the engine hardware is limited only

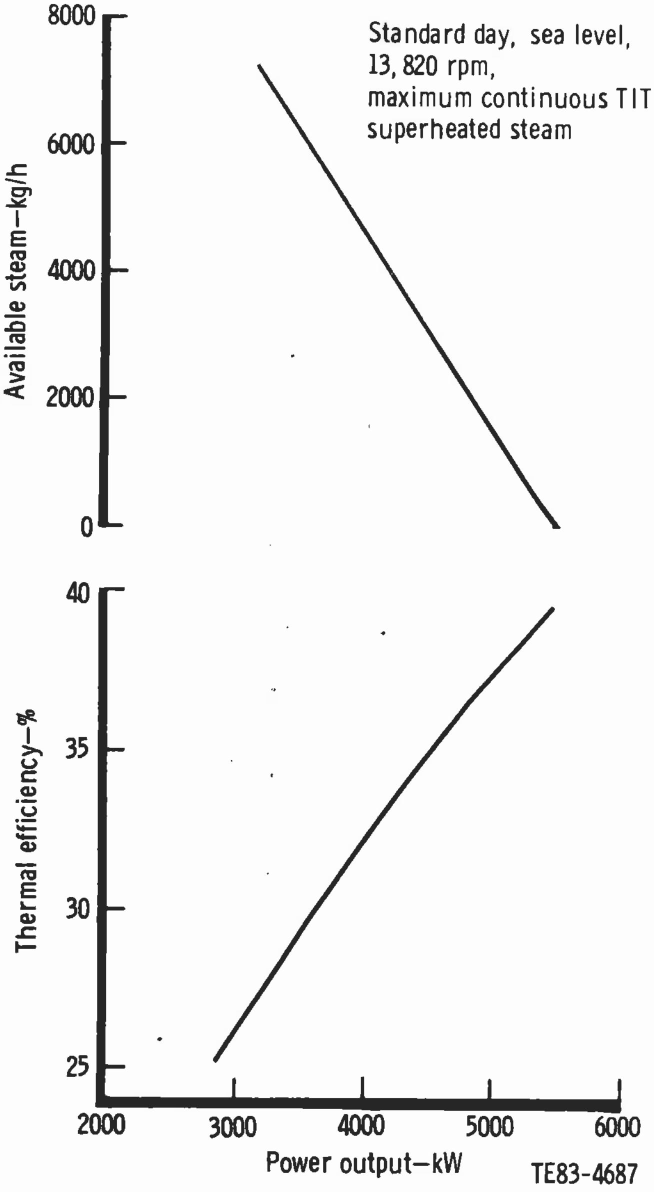


Figure 9. Available steam and thermal efficiency for Configuration IV using Model 501-KB engine.

Table III.
Effect of reheat between turbine exit and boiler for Model 501-KB engine.

Conditions: Standard day, sea level, continuous rated temperature, 13,280 rpm, reheat to 760°C exhaust temperature. Thermal efficiency is based on heat input and power output and does not include accounting for steam.

	Configuration							
	Dual Fluid Cycle (DFC)—I		Cogeneration (Cogen)--II		Combined Cycle (CC)--III		DFC and Cogen--IV	
Reheat	Off	On	Off	On	Off	On	Off	On
Steam quantity—kg/h								
Used by engine	9,000	12,400	0	0	0	0	4,250	4,740
For steam turbine	0	0	0	0	7,360	13,580	0	0
Available	0	0	7,360	13,580	0	0	3,760	7,520
Output								
Power--kW	5,400	6,100	3,200	3,200	4,220	4,900	4,300	4,300
Thermal efficiency--%	39.7	38.7	27.7	27.7	36.6	31.7	34.2	26.2

by surge margin and combustor stability. Allison's experience has shown that these limits are not restrictive on the Model 501-KB engine.

While Allison is very encouraged by the testing accomplished to date, it is fair to predict that gas turbines having a more limited surge margin may not benefit by the comparatively massive injection of steam. It should also be mentioned that some gas turbines may require extensive mechanical alterations to accommodate the 60% increase in torque capacity. There is, in addition, some concern about the deposition of dissolved solids on turbine blades.

In 1984 these and other imponderables may be answered. Several DFC cogeneration plants are scheduled for start-up in California, where the local electric utilities are actively encouraging cogeneration and one in particular is planning a DFC installation.

Further, one might speculate that a high stream injection rate may continue to show NO_x suppression benefits or that added steam injection may tend to lower turbine airfoil surface metal temperature.

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