

DUAL-FLUID CYCLE

Test Results of a Steam Injected  
Gas Turbine to Increase Power and  
Thermal Efficiency

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# TEST RESULTS OF A STEAM INJECTED GAS TURBINE TO INCREASE POWER AND THERMAL EFFICIENCY

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## ABSTRACT

The desire to increase both power and thermal efficiency of the gas turbine (Brayton cycle) engine has been pursued for a number of years and has involved many approaches. The use of steam in the cycle to improve performance has been proposed by various investigators. This was most recently proposed by International Power Technology, Inc. (IPT) and has been tested by Detroit Diesel Allison (DDA), Division of General Motors. This approach, identified as the Cheng dual-fluid cycle (Cheng/DFC), includes the generation of steam using heat from the exhaust, and injecting this steam into the engine combustion chamber. Test results on an Allison 501-KB engine have demonstrated that use of this concept will increase the thermal efficiency of the engine by 30% and the output power by 60% with no increase in turbine inlet temperature. These results will be discussed, as will the impact of steam rate, location of steam injection, turbine temperature, and engine operational characteristics on the performance of the Cheng/DFC.

## INTRODUCTION

The quest to increase power and thermal efficiency of the Brayton cycle engine has encompassed a variety of approaches since the gas turbine was first used as a prime source of power.

Various components have been added to the basic simple cycle engine to increase either power or thermal efficiency. Examples include use of a reheat burner between the turbines to increase power. This, however, results in a decrease in thermal efficiency. Regeneration from the transfer of exhaust heat to the compressor discharge air improves thermal efficiency but reduces the power output from added pressure loss in the system. Intercooling during the compression process offers another means to increase power resulting from reduced work of compression. The additional fuel required to compensate for the increased temperature rise of the burner, however, results in little if any improvement in thermal effi-

ciency. Another method outside the basic cycle selection is the addition of a waste-heat recovery system to the gas turbine, resulting in a so-called combined cycle. This approach will result in both increased power and thermal efficiency but also requires, in addition to the boiler in the exhaust, a steam turbine to extract power from the steam.

Each of the above approaches, and combinations thereof, result in varying degrees of complication to the engine system. A different approach to the problem of increasing both power and thermal efficiency has recently been proposed by IPT and tested by DDA. This system is identified as the Cheng or dual-fluid cycle (Cheng/DFC)\* and is characterized by using the exhaust heat to generate steam which is injected into the combustor to produce an increase in power and thermal efficiency without the requirement to increase the turbine inlet temperature.

The Cheng/DFC is a combination of both the Brayton and Rankine cycles. Two fluids, air and steam, are initially handled separately and then are mixed. The steam is generated by a boiler located in the turbine exhaust as it would be in a typical combined cycle. This steam is then mixed with the air and fuel of the gas turbine in the combustion chamber. The combined fluid then expands through the Brayton cycle turbine to produce power to drive the compressor and load.

## COMPARISON OF VARIOUS CYCLES

A more complete understanding of the previously discussed options for improving performance of the simple cycle gas turbine can be obtained by referring to Figure 1. This bar chart shows the performance potential in terms of specific output and thermal efficiency of the different gas turbine cycle options available with the incorporation of added components, such as a heat exchanger, intercooler, or a second burner. The bar at the far left represents the simple cycle. The bar on the right represents the Cheng/DFC. The seven bars between show the effect of using all the available combinations of regeneration, intercooling, and reheat. Three parameters are shown on Figure 1: compressor pressure ratio, thermal efficiency, and specific output.

\*Dr. Dah Y. Cheng of IPT.

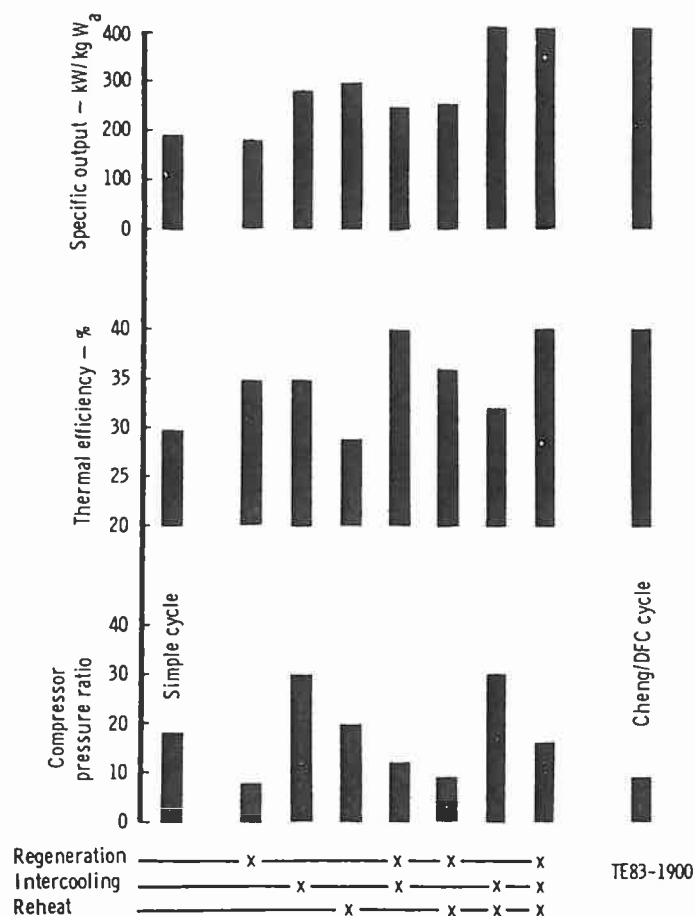


Figure 1. Performance comparison of various cycle options: constant turbine temperature, efficiencies, losses.

For any gas turbine cycle, there exists a compressor pressure ratio that results in the maximum thermal efficiency for the turbine inlet temperature being considered. It is this pressure ratio that is shown in Figure 1 for all cases except the Cheng/DFC. In this case, it is for an existing engine, as will be discussed later. By the same token, the thermal efficiency shown is the maximum attainable for the selected turbine inlet temperature cycle losses and efficiency assumptions. The Cheng/DFC produces a level of thermal efficiency equal to or greater than any other cycle option. In terms of specific output, two cycles were equal to and none exceeded the output of the Cheng/DFC.

A final consideration is compressor pressure ratio. All of the configurations, except the regeneration cycles, require a pressure ratio equal to or higher than that of the Cheng/DFC shown. The increased pressure ratio requirement of the other configurations adds a degree of complexity to these engines which is over and above the additional components required to attain the higher level of performance. This higher compressor pressure ratio would require added stages and very often variable geometry and/or bleed to provide acceptable surge-free operation in the compressor.

The most important feature of the comparisons in Figure 1 is that performance improvement from

the Cheng/DFC used here applies to converting an existing production engine, the Allison 501-KB, to the Cheng/DFC configuration. The predicted increase in thermal efficiency in this case is from 29% to 41%. Calculations show, however, that the thermal efficiency of the Cheng/DFC increases with increasing design compressor pressure ratio and turbine inlet temperature. It is possible to attain thermal efficiencies in excess of 50% at practical levels of compressor pressure ratio and turbine temperature.

In summary, when comparing the Cheng/DFC with other variants or cycle options, the Cheng/DFC will provide a level of thermal efficiency equal to or greater than any other cycle when using current state-of-the-art existing engine technology.

#### CHARACTERISTICS OF CHENG/DFC CYCLE

The Cheng/DFC concept as noted has been applied to the Allison Model 501-KB engine. This engine is a single-spool, 9.6 pressure ratio engine operating at a turbine temperature of 983°C for the continuous rating. When applied to this engine, the Cheng/DFC will increase the thermal efficiency by more than 40% over that of the basic engine, while at the same time, increasing the power output by up to 65% with no increase in turbine inlet temperature.

The source of the increase in power and thermal efficiency in the Cheng/DFC can be seen by referring to Table I. This table is the result of the thermodynamic calculations using a mathematical model of the cycle for the Model 501-KB engine at a given turbine inlet temperature. The model includes the mixing of the fuel, air, and steam and accounts for the properties of this mixture in the calculation of the expansion process through the turbine. The correlation of the model to the test results on the engine will be discussed along with the engine test data. The first case in Table I (Model 501-KB) shows the standard engine and the second is this engine incorporating the Cheng/DFC concept in which 2.5 kg/sec of steam generated by the exhaust heat is readmitted to the cycle in the combustor.

The temperature drop across the turbine is essentially the same for both cases. However, the power produced by the turbine is equal to the product of the mass flow, specific heat, and temperature drop times a constant:

$$\text{Power} = W_g \times C_p \times \Delta T \quad 0.7456 \times 778/550 \text{ kW}$$

As shown, the output power of the turbine with steam increases by more than 30%. Approximately half of the increase results from the increase in specific heat; the other half from the added mass flow. This increase is equal to 2789 kW for the case being considered. The added power required by the compressor is 514 kW, leaving an increase of 2275 kW as available output power. This is a 64.9% increase in the output power. A 17.8% increase in fuel flow is required to bring the steam up to the turbine inlet temperature.

Table I.  
Allison Model 501-KB Cheng/DFC (standard day, sea level),  
turbine inlet temperature constant, turbine back pressure constant,  
rpm constant.

	Model 501-KB	Cheng/DFC	Difference	Percent change
Steam flow--kg/sec	0	2.5		
Output power--kW	3,504	5,778	2,275	64.9
Thermal efficiency	29.1	40.7		39.9
Fuel flow--kg/hr	1,016	1,197		17.8
Inlet airflow--kg/hr	15.0	14.7		
Turbine mass flow--kg/hr	14.7	16.9		15.0
Compressor pressure ratio	9.6	11.6		
Compressor power--kW	4,757	5,271	514	
Turbine power--kW	8,261	11,050	2,789	33.7
Average specific heat of turbine expansion--kJ/kg °C	1.122	1.293		15.3
Temperature drop across turbine, $\Delta T$ --°C	474	480		

The net result is an improvement in thermal efficiency of 39.9%.

The Cheng/DFC can be applied to either a single-shaft engine, such as the Allison Model 501-KB, or a dual-shaft configuration of the same engine identified as the Model 501-KF. The results, however, differ because of the way in which each engine operates when the mass flow through the turbine is increased. The operating lines on the compressor map for the two engines are shown on Figure 2. This figure assumes the same engine geometry as the current engine. When the mass flow through the turbine is increased by the addition of steam, the pressure ratio increases along the speed line (This is a constant speed engine) on the Model 501-KB engine. Both the pressure ratio and speed increase in the dual-shaft Model 501-KF engine with the steam added to the turbine flow. The compressor of the Cheng/DFC engine requires adequate surge margin to accommodate the increase in pressure ratio resulting from the steam. This is available in the Model 501-KB and the Model 501-KF engines.

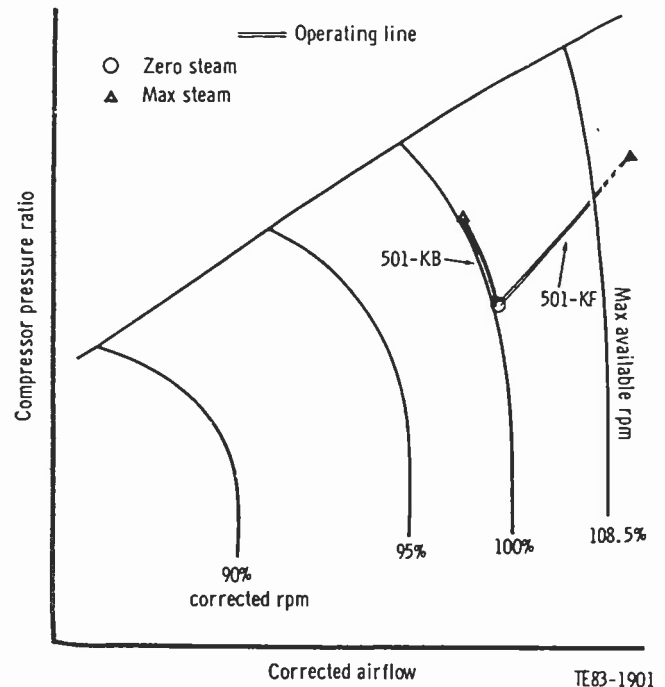


Figure 2. Operational characteristics of Cheng/DFC on the compressor map.

Cheng/DFC up to a limit defined as maximum steam flow. The line of maximum steam flow is a function of the boiler design as well as the assumed temperature difference between the exhaust gas and the steam.

Figure 4 shows the Cheng/DFC performance is restricted on the dual-shaft Model 501-KF engine by a mechanical speed limit of 108.5% of the rated rpm. When this is imposed on the operation with the Cheng/DFC, the maximum increase in output

A matrix of the performance potential incorporating the Cheng/DFC in either the Allison Model 501-KB or -KF engines is shown in Figures 3 and 4 for the two engines respectively. In both these figures, the base point is 983°C turbine inlet temperature. The effect of changing turbine temperature and/or steam rate on the output power and thermal efficiency can readily be seen.

The lines labeled zero stream flow on Figures 3 and 4 are the typical throttle lines for a base-line, simple cycle Model 501-KB and 501-KF engine, respectively. Arbitrary amounts of steam were added to the engine at each of four turbine inlet temperatures to define the performance of the

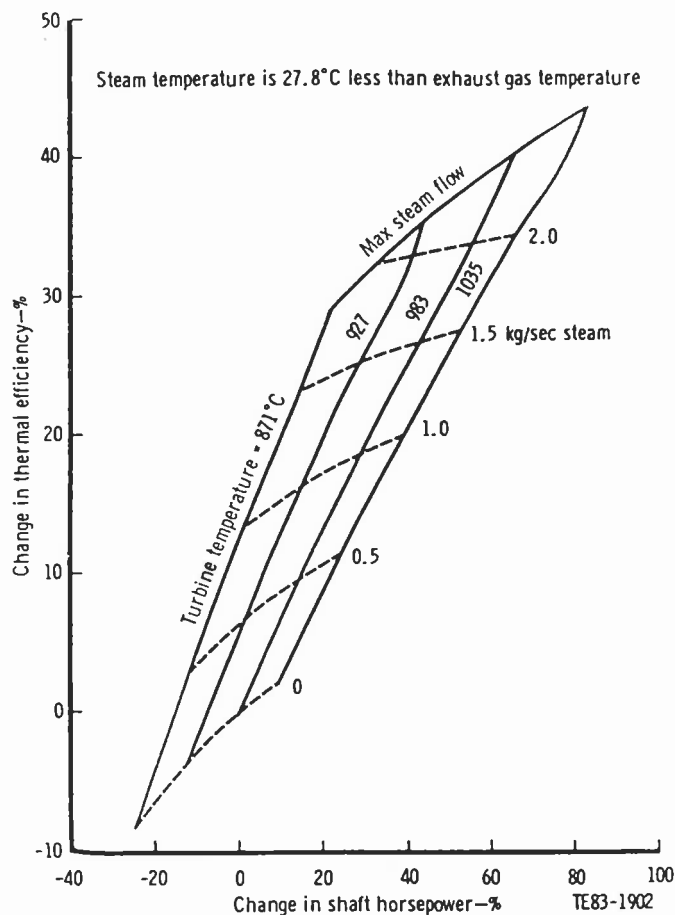


Figure 3. Allison Model 501-KB engine, Cheng/DFC, standard day, sea level, 13,820 rpm.

power is limited to 30%. At the maximum steam rate, the improvement in thermal efficiency is also limited to 30% by this speed limit. While these gains are significant, they are less than those of the Model 501-KB engine. For this reason, the Model 501-KB engine was selected for a full-scale engine test demonstration of the Cheng/DFC concept, which will be described later.

An analytical comparison has been made between the Cheng/DFC engine, the Model 501-KB engine, and a high-performance, more advanced technology simple cycle engine to show the flexibility and throttling characteristics of the different engines.

A hypothetical requirement for a continuous power output of 5370 kW was assumed. Power requirements down to 50% power, 2685 kW, and the requirement for process steam were also considered. The results of this analysis will be discussed using Figure 5 and Table II.

The Allison Model 501-KB has a continuous rating of 3260 kW, and thus will not meet the 5370 kW requirement. This is point B on Figure 5. With the incorporation of a steam manifold around the combustion case and an exhaust heat boiler, the engine can be converted to a Cheng/DFC engine and would, at the continuous rating and selected

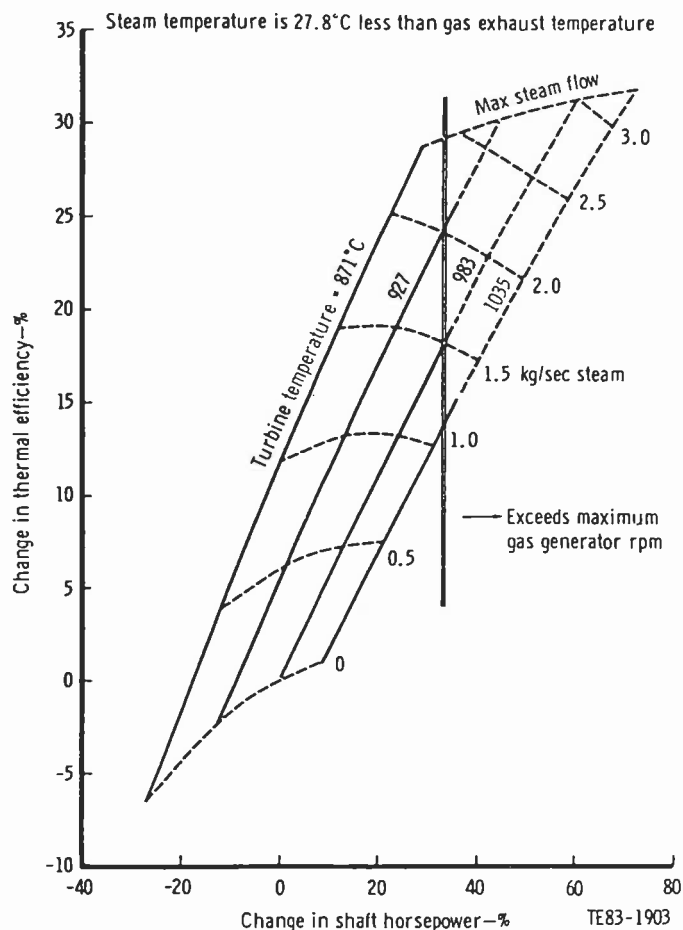


Figure 4. Allison Model 501-KF engine, Cheng/DFC, standard day, sea level, 13,820 output rpm.

steam flow, produce 5370 kW. This is point C on Figure 5. At the same time, the thermal efficiency would increase from 28% to 39.5%.

The more advanced technology, high-performance simple cycle engine selected for comparison incorporated an increased compressor pressure ratio compressor and operated at increased turbine inlet temperature. This resulted in a thermal efficiency at the continuous rating of 5370 kW equal to 29.5%. This is point A on Figure 5. This efficiency is 10% less than the Cheng/DFC value of 39.5%. These data are listed under case 1 on Table II and show that the Model 501-KB Cheng/DFC provides a 25% fuel saving over the high-performance engine at the 5370 kW output.

Throttling of the Cheng/DFC can be accomplished in two ways. One is by reducing turbine temperature and holding the steam flow constant. The second is to decrease the steam rate at constant turbine temperature. The first of these two approaches results in the attainment of maximum thermal efficiency and is based on the engine using maximum steam flow. The second, while not providing as high a thermal efficiency as the first at throttled power, does have the ability to provide excess steam for any desired use. Two throttled points are compared at 75% (4020 kW) power on Figure 5 and Table II as cases 2 and 3.

Table II.  
Performance comparison--Cheng/DFC throttled Model 501-KB  
performance vs high-performance simple cycle.

Case	1	2	3	4
Output power--kW	5370	4020	4020	2685
Power--%	100	75	75	50
Model 501-KB (Cheng/DFC)				
Process steam--kg/hr	0	0	5400	0
Thermal efficiency	39.5	37.0	32.4	32.0
High-performance simple cycle				
Thermal efficiency	29.5	30.0	30.0	28.0
Fuel savings for Model 501-KB Cheng/DFC over high-performance simple cycle--%	25.0	18.9	7.5	11.9

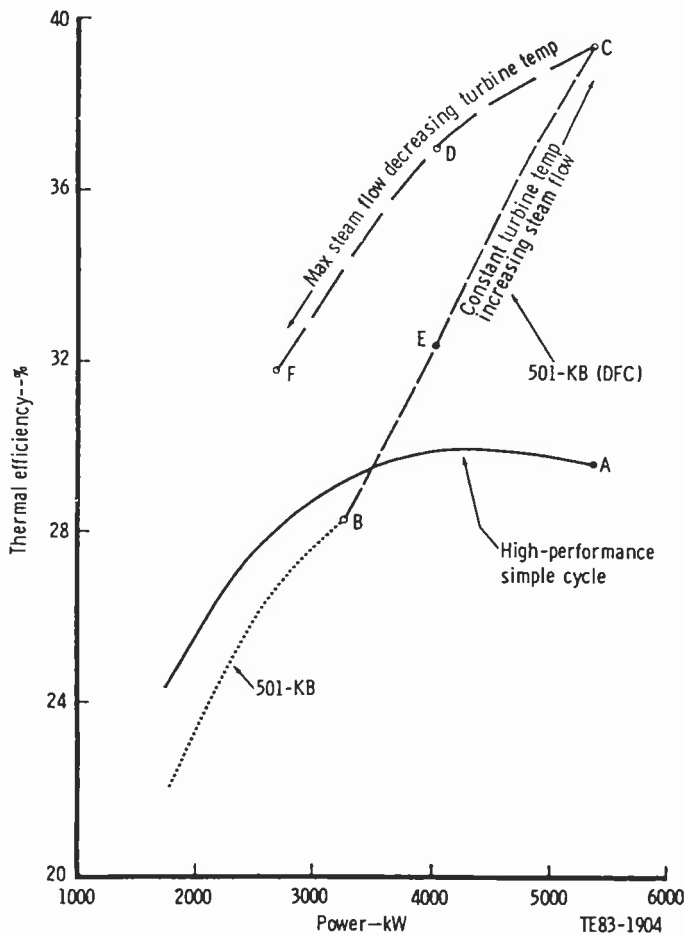


Figure 5. Comparison of Models 501-KB/501-KB (Cheng/DFC) and a high-performance simple engine, standard day, sea level.

Point D, case 2, provides 37% thermal efficiency and results in the engine operating at 871°C turbine temperature and 1.8 kg/sec steam flow with all the steam being used by the engine. Point E, case 3, while providing the same power, operates at 983°C turbine temperature and only uses 0.7 kg/sec of the steam being generated from the exhaust heat. As shown in Table II, this will leave

1.5 kg/sec or 5400 kg/hr of process steam available for other purposes.

A final consideration from examination of Figure 5 is the thermal efficiency at the 50% power condition, point F on Figure 5. The Cheng/DFC results in a thermal efficiency at this condition of 32% when operating with the maximum steam flow, which is 1.3 kg/sec. This thermal efficiency compares with 26.5% for a standard Model 501-KB or 28% for the high-performance engine at this power level, as shown on Table II.

The bottom line of Table II shows the percent of fuel savings of the Cheng/DFC over the high-performance engine for the four cases discussed. The savings in fuel can be seen to be from 7.5% to 25.0%, depending on the power requirement and method of operation.

A further characteristic of the Cheng/DFC, which results in additional flexibility to a total system, is that steam from a source other than that generated by the engine can be used to increase the thermal efficiency and power output of the engine. In an overall system then, where steam is available from some other source, the combined power and steam requirements can be met in a number of ways by selecting the best compromise for the source and quantity of steam to meet the overall plant requirements while operating at the maximum plant efficiency.

The Cheng/DFC concept, while thermodynamically sound, remained to be demonstrated to prove the practicality of the concept. Questions about possible change in combustion efficiency with steam in the burner, about how the steam should be introduced into the combustion chamber, and about the limits of steam flow before quenching might occur could only be answered by actual testing of the full-scale engine. The question of generating steam with the exhaust heat was not of concern, since this is a well-demonstrated concept.

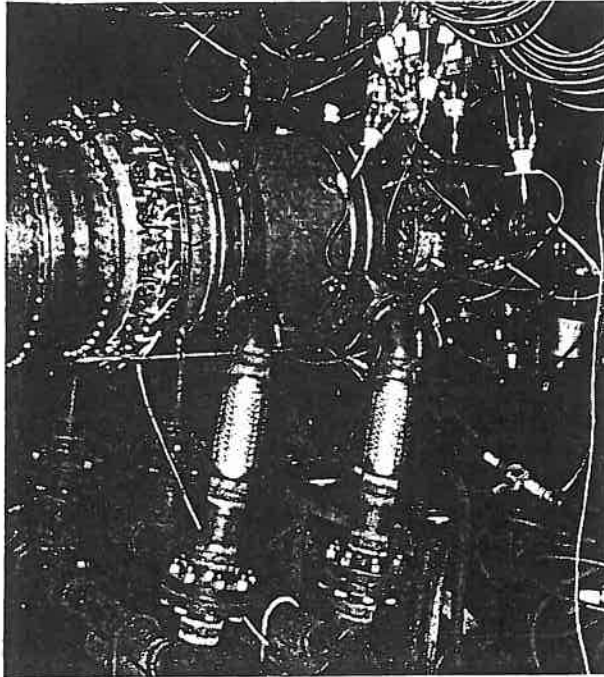


Figure 6. Steam connections to the Cheng/DFC engine manifolds.

#### DESCRIPTION OF TEST SETUP AND PROCEDURE

As noted previously, a Model 501-KB engine was selected for the full-scale demonstration of the Cheng/DFC concept. The only change in the engine from the standard configuration was to incorporate two steam manifolds around the outer combustion case.

The Model 501-KB combustor is a can-annular configuration with six burner cans. The cans are 63.5 cm long and are enclosed by the outer combustion case. Injection of steam into the combustor was accomplished by reworking the outer combustion case to provide two steam manifolds around the case with 4.5-cm diameter holes in the case under each manifold. The holes were equally spaced and located to introduce steam between the individual cans. The forward manifold was located at the burner inlet, i.e., the plane of the fuel nozzles, and the rear manifold was located 35.6 cm aft of the front manifold. The steam was supplied to each manifold by two diametrically opposed inlets, each 9.1 cm in diameter. The manifolds were designed to allow the total desired quantity of steam to be supplied by either manifold. Thus the effect of location of injection of the steam could be examined. Figure 6 is a picture of the engine installed in the test stand showing the two steam manifolds around the combustion case.

The engine was tested with the inlet air supplied from a facilities source where the inlet conditions could be held to a standard of 15°C and 101.33 kPa for all the testing. This eliminated the need to correct the data for inlet pressure and temperature. The engine exhaust was ducted to ambient.

The steam was supplied to the engine from an external source at a temperature of 205°C and a pressure consistent with the combustion chamber pressure where the steam was introduced. The combustion chamber pressure, and thus the steam pressure, varied between 930 kPa and 1070 kPa during this testing. The steam had about 10°C to 20°C of superheat.

The Model 501-KB engine normally operates to a combustor outlet temperature measured by electrically averaging nine sampling-type thermocouples. The engine control system is designed to hold the engine rpm at the desired value and to supply fuel as required to run to any desired thermocouple temperature,  $T_c$ . In addition to the above standard instrumentation at the inlet to the turbine, a partial survey of the turbine inlet temperature was taken for each steam flow using four element rakes at each of three circumferential positions in one section of the annulus. These data would provide information to determine if any adverse temperature profiles resulted from the steam ingestion.

The test schedule for the Model 501-KB Cheng/DFC engine included operating the engine over a range of turbine inlet temperatures from 800°C to 1040°C at steam flows of 0 kg/sec to 2.3 kg/sec, with all the steam being injected in either the front or rear manifold or equally divided between the two. This resulted in three cases in which the performance for a range of turbine temperature can be examined. These three cases are listed in Table III.

Table III.  
Test cases to be examined.

Case	% steam flow	
	Front	Rear
A	100	0
B	0	100
C	50	50

The thermocouple system, as described previously, provided one means to monitor turbine inlet temperature. A second means to determine this temperature is to calculate the value from the airflow and fuel flow. Experience with Model 501 series engines has shown that there is a difference between the thermocouple and calculated fuel-air temperature at turbine inlet, which is a function among other factors of the flow into the turbine. With the injection of steam in the combustor, both the flow and the temperature profile of the gas into the turbine are subject to distortion, and thus it was deemed desirable to use the calculated fuel-air turbine inlet temperature for the evaluation of the engine performance. This would ensure the observed performance changes were only a result of the steam flow.

#### TEST RESULTS

Table IV is a summary of the data points that were run with the steam. In addition to these points with steam, a zero steam calibration was run

Table IV.  
Cheng/DFC test demonstration points--turbine  
inlet temperature 800°C to 1040°C, N = 13,820 rpm,  
standard day, sea level.

Case	Figure No.	No. of data points	Quantity of steam injected--kg/sec	
			Front manifold	Rear manifold
A	7-10	3	0.45	0
		4	1.00	0
		6	1.60	0
		4	2.30	0
B	8-11	4	0	1.00
		6	0	1.60
		6	0	2.30
C	9-12	4	0.45	0.45
		6	0.80	0.80
		6	1.15	1.15

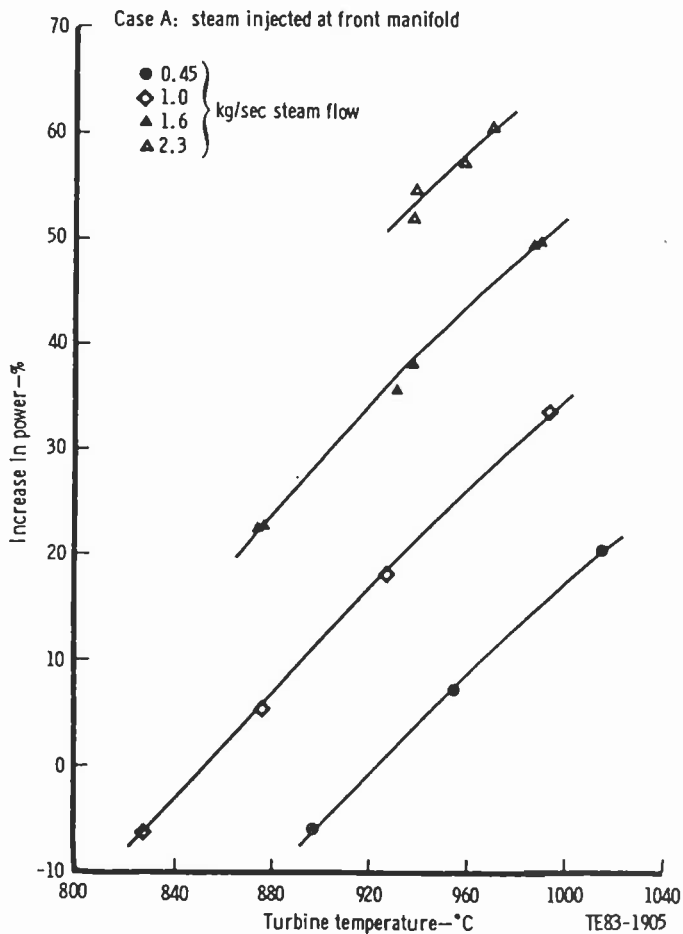


Figure 7. Allison Model 501-KB engine, Cheng/DFC test results, standard day, sea level, 13,820 rpm.

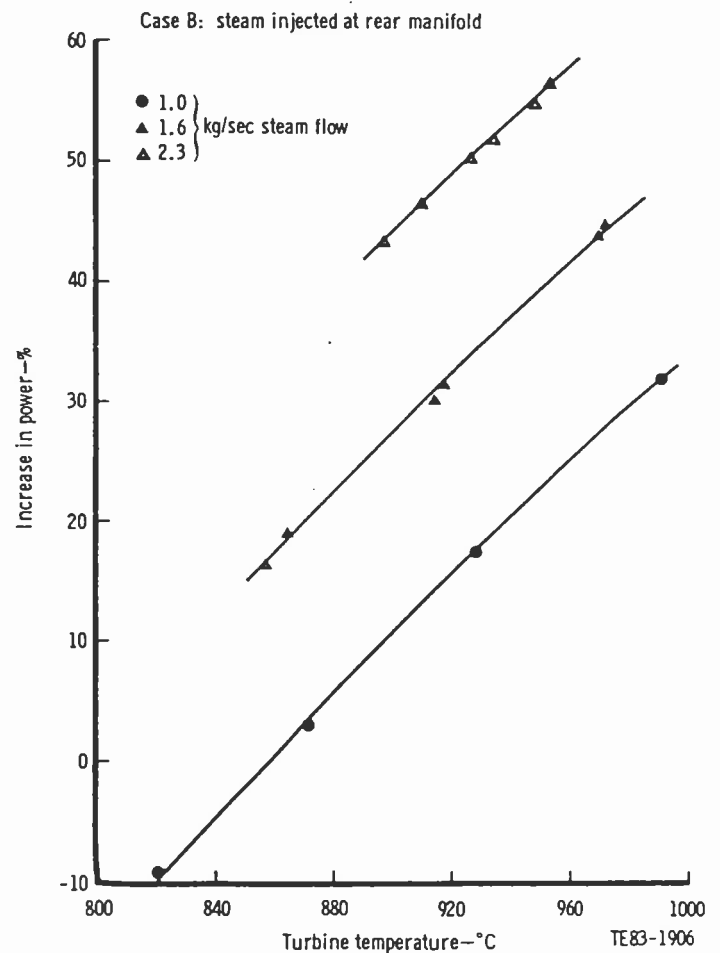


Figure 8. Allison Model 501-KB engine, Cheng/DFC test results, standard day, sea level, 13,820 rpm.

both before and after the operation with steam. Examination of the test results can best be done by looking at the increase in both power and thermal efficiency as a function of turbine temperature and steam flow rate. These data are presented in Figures 7 through 12.

Figures 7, 8, and 9 show the demonstrated increase in power output of the Cheng/DFC test engine as a function of steam flow and turbine temperature, where 100% power is defined as the power at 983°C turbine temperature with zero steam flow. Figures 7, 8, and 9 are for cases A, B,



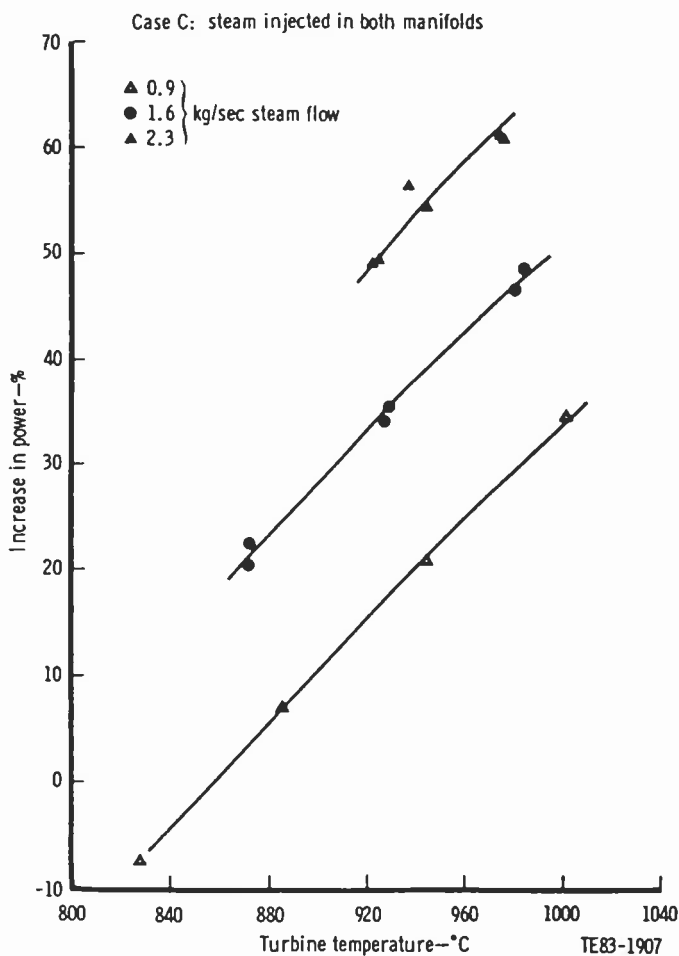


Figure 9. Allison Model 501-KB engine, Cheng/DFC test results, standard day, sea level, 13,820 rpm.

and C respectively. It can be seen that at 983°C turbine temperature and 2.3 kg/sec of steam flow, there is a 60% increase in power, regardless of the location of the steam injection. It can also be seen (and will be discussed later) that the location of the steam injection had little impact on the power output for any of the steam flows investigated.

Figures 10, 11, and 12 are companion plots to the preceding plots to show the improvements in thermal efficiency with steam ingestion. Here again the 100% value was selected at 983°C turbine temperature and zero steam flow. The increase in thermal efficiency can be seen to be up to 28% for case C, where 1.15 kg/sec of steam were injected through each manifold simultaneously.

Figure 13 is a cross plot of Figures 7, 8, and 9 at a turbine temperature of 983°C, with a line superimposed showing the expected output based on calculated performance of the cycle with steam. Two results from this testing can be seen here. The first is that the change in power, by introducing steam at the different manifold locations, i.e., case A vs B vs C, is small and within the expected accuracy of the test results. This means that until or unless other testing is done, a case cannot be made for use of one manifold over the other.

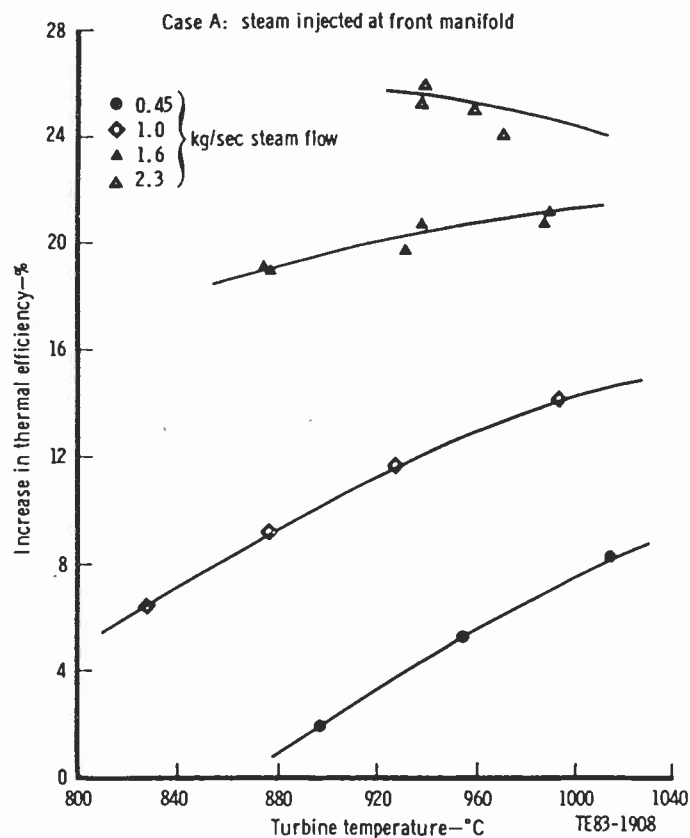


Figure 10. Allison Model 501-KB engine, Cheng/DFC test results, standard day, sea level, 13,820 rpm.

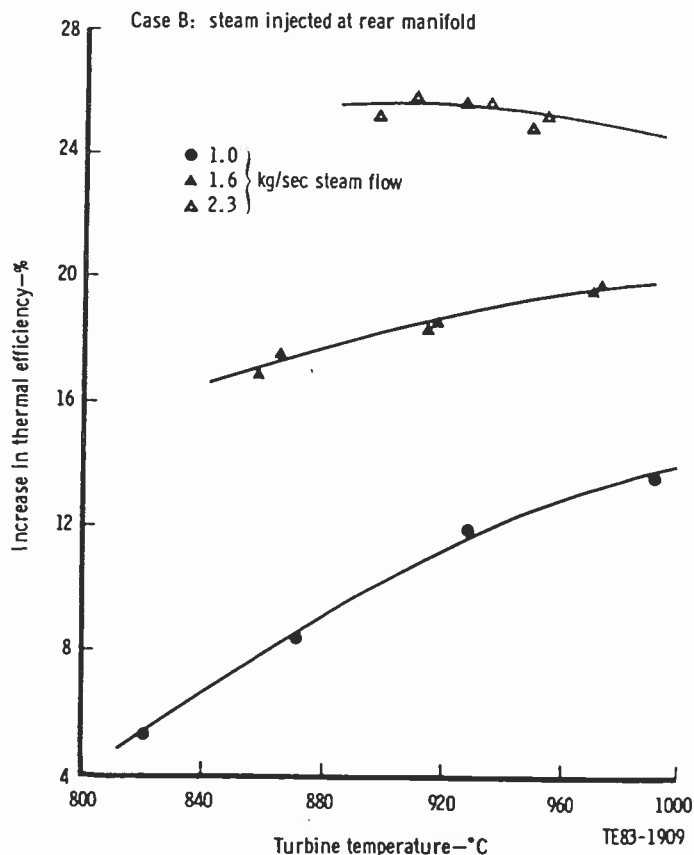


Figure 11. Allison Model 501-KB engine, Cheng/DFC test results, standard day, sea level, 13,820 rpm.

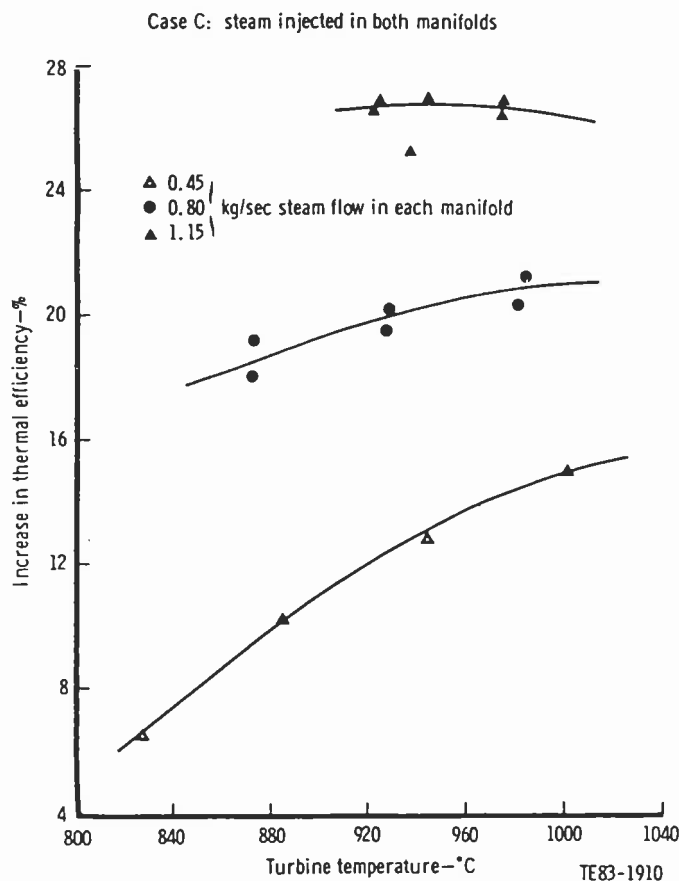


Figure 12. Allison Model 501-KB engine, Cheng/DFC test results, standard day, sea level, 13,820 rpm.

The second feature of this figure is that, in general, test results verified the predicted power augmentation with steam as evidenced by the analytical data superimposed on the test results. This analytical line on Figure 13 was taken from Figure 3. The test data do, however, show a 1% to 3% reduction in augmentation from the analytical data at 2.3 kg/sec of steam flow. A possible explanation for this would be a slight reduction in turbine efficiency caused by the change in gas composition and high turbine mass flow rate at this condition. The analytical model assumed a constant efficiency, and the turbine design did not consider steam as part of the working fluid. The test engine did not include instrumentation to determine turbine efficiency; however, even with such instrumentation, the small change in efficiency would be difficult to measure.

Figure 14 is similar to that of Figure 13 except it shows the characteristic of thermal efficiency as a function of steam flow and location of injection. The test results show here that the two manifold systems (case C) result in an improvement in thermal efficiency over that of either single manifold. The explanation for this could be that the combustion efficiency is adversely affected with the single manifold operation but not when using both manifolds simultaneously. This must only be conjecture, since no data were taken to evaluate combustion efficiency during the test.

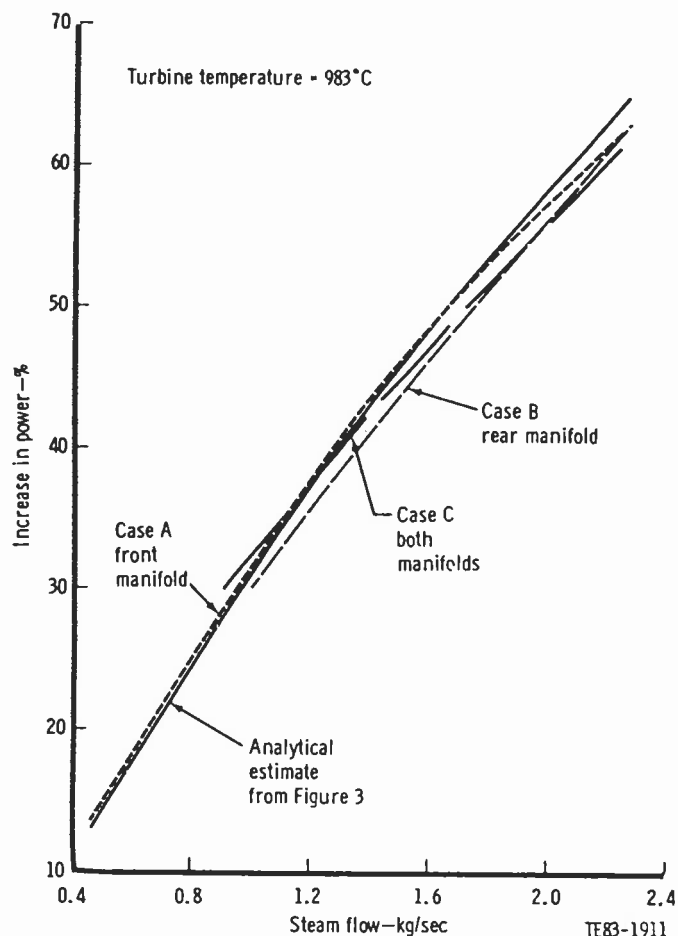


Figure 13. Allison Model 501-KB engine, Cheng/DFC test results, standard day, sea level, 13,820 rpm.

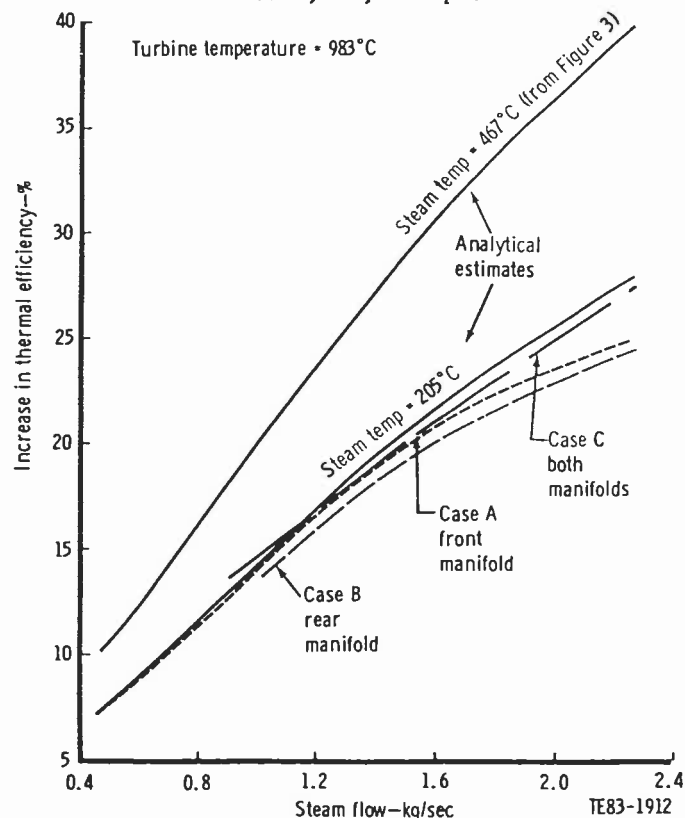


Figure 14. Allison Model 501-KB engine, Cheng/DFC test results, standard day, sea level, 13,820 rpm.

As was the case with the power output, the analytical result is superimposed on the thermal efficiency plot. It is necessary here, however, to include two sets of analytical data because steam temperature affects thermal efficiency. This is not true for power. The higher line on Figure 14 is from Figure 3 and, as noted, is for a steam temperature of 467°C. Since the test was run with 205°C steam, an analytical calculation was made for the test steam temperature of 205°C. These data are compared with the test results. The correlation of this calculation to the case C test results is very good.

It can be concluded from Figures 13 and 14 that within a reasonable degree of accuracy, the behavior of the Model 501-KB engine with steam injection is predictable with a thermodynamic model of the cycle that incorporates the properties of steam.

As noted previously, the test of the Cheng/DFC engine included additional instrumentation to evaluate the temperature profile at the inlet to the turbine. This was necessary to ensure that with steam injection, the temperature profile would not be distorted in a way to produce an adverse effect on the turbine. Since the Cheng/DFC runs to the same turbine temperature as the current engine, there would not be any concern about the turbine if the profile with and without steam were the same. As shown in Figure 15, the radial temperature gradient with 0, 1.6, and 2.3 kg/sec of steam injected in both manifolds is in fact very nearly the same. A similar characteristic was observed for steam injected in either the front or rear manifold. Based on these results, there is no concern about the turbine temperature profile with the injection of steam.

A post-test zero steam performance calibration was run on the engine prior to removal and inspection. These data were compared with the initial engine calibration prior to steam ingestion. No change in performance could be seen between the two calibrations. Although this testing to evaluate performance characteristics of the Cheng/DFC was of short duration compared with typical industrial use, there is no evidence to suggest that operation with steam in the products of combustion would cause any change in depreciation with operating time over that associated with the standard engine.

The results of this testing have demonstrated the feasibility of the Cheng/DFC and have answered many of the questions that were posed prior to this effort. There does not seem to be any major effect on the combustion efficiency with steam in the combustor. Although the combustion efficiency was not measured, the correlation of the calculated and the measured performance will support this conclusion.

Using this combustion configuration, i.e., the Model 501-KB can-annular type burner, the

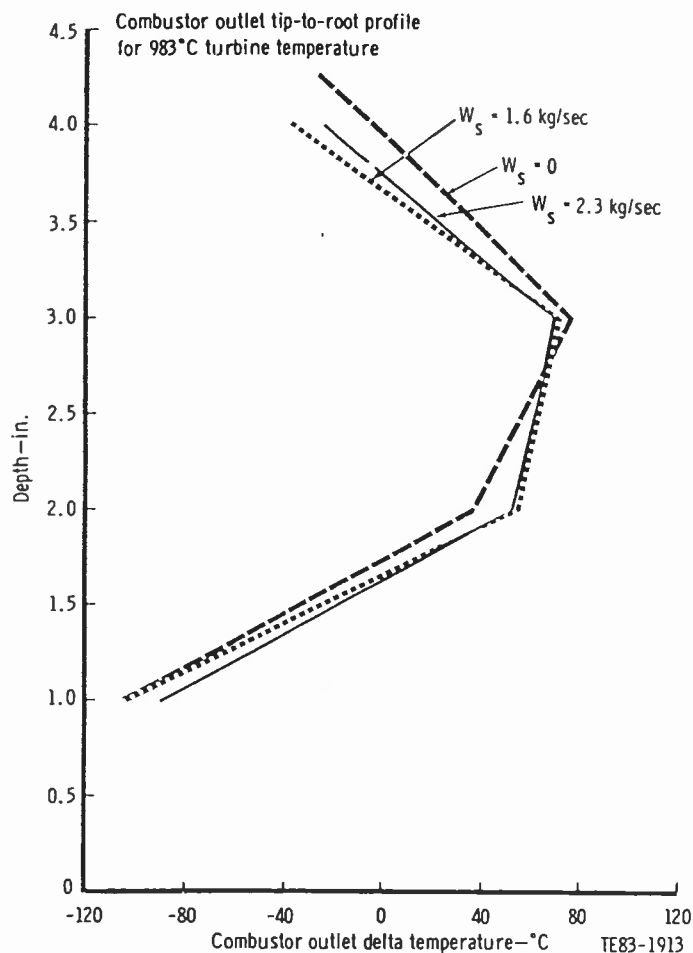


Figure 15. Allison Model 501-KB engine, Cheng/DFC test results, standard day, sea level, 13,820 rpm.

power output is relatively insensitive to the location of the steam injection. The difference in performance between introducing all the steam forward, or aft, or equally split between two manifolds, was not significant.

This testing was done using DF-2 fuel only. Based on experience with water injection for NO<sub>x</sub> reduction, however, there is no reason to believe that a Cheng/DFC gas-fired or dual-fuel engine configuration would not respond in a like manner. Calculations show that a methane-fueled Cheng/DFC engine operating at the same turbine temperature and maximum steam flow would produce 2.6% more power than the liquid-fueled engine in the single-shaft Model 501-KB configuration and 1.5% more in the dual-shaft Model 501-KF engine. The corresponding changes in thermal efficiency would be 0.7% for the 501-KB and no change in the case of the 501-KF.

The testing reported here did not include the measurement of exhaust emissions because the temperature of the steam, as noted previously, was not high enough to produce the maximum thermal efficiency. Therefore the usefulness of the

emission data would be limited. However, analytical calculations would indicate and experience would show that the introduction of steam will be in the direction of reducing the level of NO<sub>x</sub> emissions.

Engine disassembly inspection following the test showed no adverse effects on the engine hardware from the steam. Those parts that were in the flow path of the steam were of particular concern; however, there was no evidence of the steam causing problems in this area.

The lubrication system, including air/oil labyrinth seals, were also examined following the operation with steam. During operation, these seals were exposed to a mixture of air and steam. As was the case with the flow path, no adverse effects were seen in these parts.

## CONCLUSIONS

After many years of effort to improve the thermal efficiency and output of the gas turbine by a number of means, the Cheng/DFC provides an answer that has considerable merit. It is a system readily adaptable to an existing engine, i.e., Model 501-KB, with the capability of increasing the thermal efficiency by 40% and the power by over 60% with no increase in turbine temperature. These gains would be difficult, if not impossible, to attain by any conventional Brayton cycle engine.

The test results presented here show that the Cheng/DFC is a viable concept and provides a readily available means to significantly improve the performance of an existing engine, the Model 501-KB.

## Cogeneration system accommodates thermal load fluctuations without economic penalty

Cogeneration is the simultaneous production of two forms of energy from one source of fuel. Typically, electricity is produced using an engine which also gives off waste heat. The waste heat is then captured to produce thermal energy for process or heating use. This simultaneous production consumes less fuel than if the two forms of energy were produced separately. However, in the pulp and paper industry the economics of cogeneration are penalized by fluctuating thermal loads since conventional cogeneration systems (simple cycle) operate most economically when the demand for thermal energy is constant over time.

International Power Technology of Sunnyvale, Calif., has developed a cogeneration system, Cheng Cycle Series Seven, which accommodates wide fluctuations in thermal load without economic penalty and without mechanical complexity. The Cheng Cycle consists of a modified Allison 501-KH gas turbine (manufactured by Detroit Diesel Allison Div. of General Motors), heat recovery steam generator, supplementary burner, gear box, electrical generator, controls, and miscellaneous equipment required to support the operations of the plant. Basically, the engine recovers energy from its own exhaust stream in the form of superheated steam and returns this energy to the turbine in a precisely controlled manner, boosting both the power output and fuel efficiency of the turbine. When process steam demand is low, the excess thermal energy is used to produce superheated steam for injection. Power output and fuel efficiency increase in proportion to the amount of steam injected. Fluctuating thermal

loads are accommodated because thermal energy not needed for process is used to increase production of electricity. The system also involves no additional mechanical complexity beyond that of conventional simple cycle gas turbine systems.

Figure 1 shows how the system is applied to cogeneration applications. Saturated steam from the drum in the waste heat boiler is taken off through two lines; one supplies process steam requirements, the other feeds the superheater. From the superheater, steam is injected into the engine in the combustor region to produce increased power, higher efficiency, and NO<sub>x</sub> emissions control. A supplementary burner added between superheater and evaporator provides increased operating flexibility by allowing peak steam demand up to 48,000 lb/hr to be supplied by a single unit.

Both conventional cogeneration arrangements and the Cheng Cycle arrangement benefit from the addition of a supplementary burner in the exhaust duct. In a conventional plant, the

burner allows production of process steam to be approximately doubled by firing directly into the turbine exhaust stream to respond to peaks in process steam requirements.

In the Cheng Cycle arrangement, the supplementary burner provides this same peak-handling benefit. In addition, the extra steam produced with the duct burner can also be injected into the turbine when it is desirable to produce additional electrical power. This feature "unlocks" the traditional cogeneration constraint wherein thermal and electrical power are linked in a one-to-one relationship.

An integral part of the Cheng Cycle Series Seven is computer-based economic control as well as overall mechanical control. In real time, the system analyzes process steam and electrical requirements vs utility buy-back rates in addition to other operating constraints. After checking against limits, the system economically optimizes the cogeneration plant while maintaining process energy requirements.

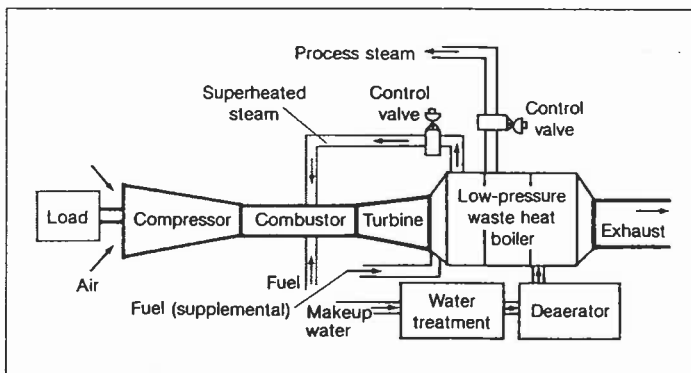


FIGURE 1:  
Cheng Cycle  
Series Seven  
applied to  
cogeneration  
systems.