Test of a Prototype Dual Fluid Cycle 501-KB Engine

Prepared for
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I. INTRODUCTION

A dual fluid engine cycle has been defined by International Power Technology, Inc., Sunnyvale, California. This dual fluid cycle (DFC) uses steam injected into the gas turbine engine combustion section and thus combines the gas turbine cycle (Brayton) and the steam cycle (Rankine) simultaneously. The Allison Model 501-KB is an ideal engine for a DFC version. Detroit Diesel Allison (DDA) fabricated the parts to convert an in-house test engine to a DFC Model 501-KB and installed a steam supply system for this demonstrator test program.

An agreement was reached with International Power Technology (IPT) to conduct a test program with a DFC configuration and report the results of this DFC testing. The goal was to test the engine with steam flows to 5 lb/sec, turbine inlet temperatures to 1800°F, and with steam injected at two locations in the combustion area. Performance and operating characteristics would be identified.

II. CONCLUSIONS

The DFC Model 501-KB engine operated satisfactorily with up to 5.0 lb/sec steam flow and with turbine inlet temperatures up to 1800°F. From the results of the test, the ideal steam injection is 50% through the front manifold and 50% through the rear manifold. At 1800°F turbine inlet temperature, the developed shaft horsepower (shp) was 158% of the baseline calibration shaft horsepower, and thermal efficiency was 124% of the baseline calibration efficiency. Further improvement is expected from operating a DFC version of a typical Model 501-KB, which uses superheated steam, rather than the specific engine tested, which used saturated steam.

Satisfactory engine operation was demonstrated. However, a production DFC Model 501-KB would require certain changes to ensure that the engine would perform reliably for normal Model 501-KB life periods with the higher DFC developed shaft horsepower values. Engineering analyses have identified the required changes, and an active program has been initiated to implement these changes for production DFC engines.

III. DISCUSSION

General Approach

The engine used for this test was an available in-house workhorse test engine, essentially a standard Model 501-KB, modified only to the extent necessary to conduct this test. The purpose of the test was not to "fine tune" the performance of the DFC but to demonstrate the feasibility of operating a Model 501-KB engine as a DFC version and to obtain general performance values, indications of most desirable steam injection methods, and general handling characteristics while operating as a DFC version.

The steam used for this test was not the high-temperature superheated steam that would be available from a waste heat boiler of an operational DFC installation. The steam from the DDA powerhouse supply was delivered to the engine at 350°F-400°F rather than above 600°F. This resulted in substantially higher fuel flows, particularly at the higher steam flows and higher turbine inlet temperature conditions. The approach was to account for this by calculation. However if the increment of fuel flow increase attributed to the lower steam temperature adversely affected combustion efficiency, this aspect was not accounted for by the calculation prodedure. This increased fuel flow due to the lower steam temperature would have grossly affected the validity of emission measurements as being representative of what would exist with superheated steam. For this reason, no exhaust emission data were recorded.

When the baseline performance calibration was performed, it was determined that the test engine was low on performance. The compressor airflow and pressure ratio were below those of a standard production Model 501-KB. The direct effects of this were taken into account during the analysis of the data. Secondary effects, such as the effect of lower pressure ratio and reduced compressor efficiency on specific fuel consumption (or thermal efficiency), were not. The approach used in analyzing the gains from DFC operation was to compare the gains from the baseline rather than the absolute performance level achieved.

Configuration

The engine used for this test was S/N ASP002, which is essentially a Model 501-KB except for the modifications for DFC testing.

COMBUSTION SECTION

The standard outer combustion case was replaced by one having two integral steam distribution manifolds. The front one was located approximately in the plane of the combustor dome. The rear one was located near the plane of the combustor dilution air holes. The outer combustion case for the DFC test is shown in Figure 1. The passages for the steam from each manifold into the combustors consisted of six holes located circumferentially midway between adjacent combustors. There were two inlet steam connections 180 degrees apart to each manifold. Figures 2 and 3 show the DFC outer combustion case installed on the engine prior to the test. The combustors installed for the test were standard Model 501-KB low-emission combustors for use with liquid fuel.

COMPRESSOR SECTION

No parts changes were made to the compressor for the test. The extent of preparing the compressor for this test was to remove the rotor and clean by seed blast all blades and vanes to remove accumulated dirt from extensive prior testing. The compressor was not refurbished. The cleaning was performed to

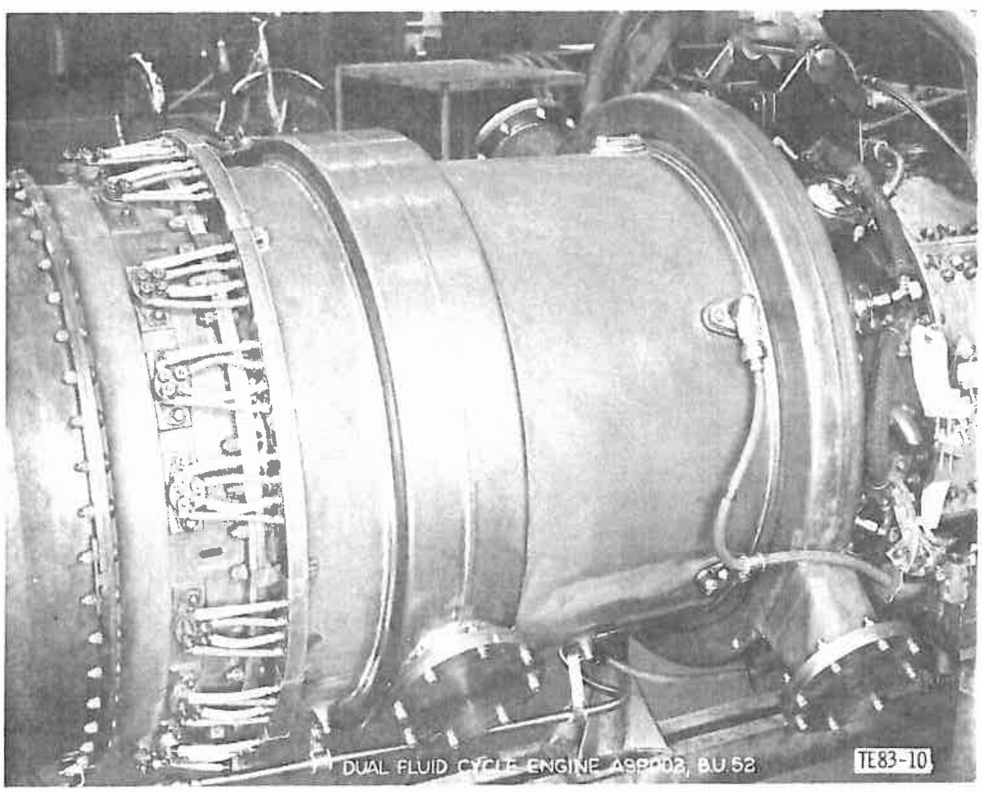

Figure 1. View of outer combustion case for DFC engine.

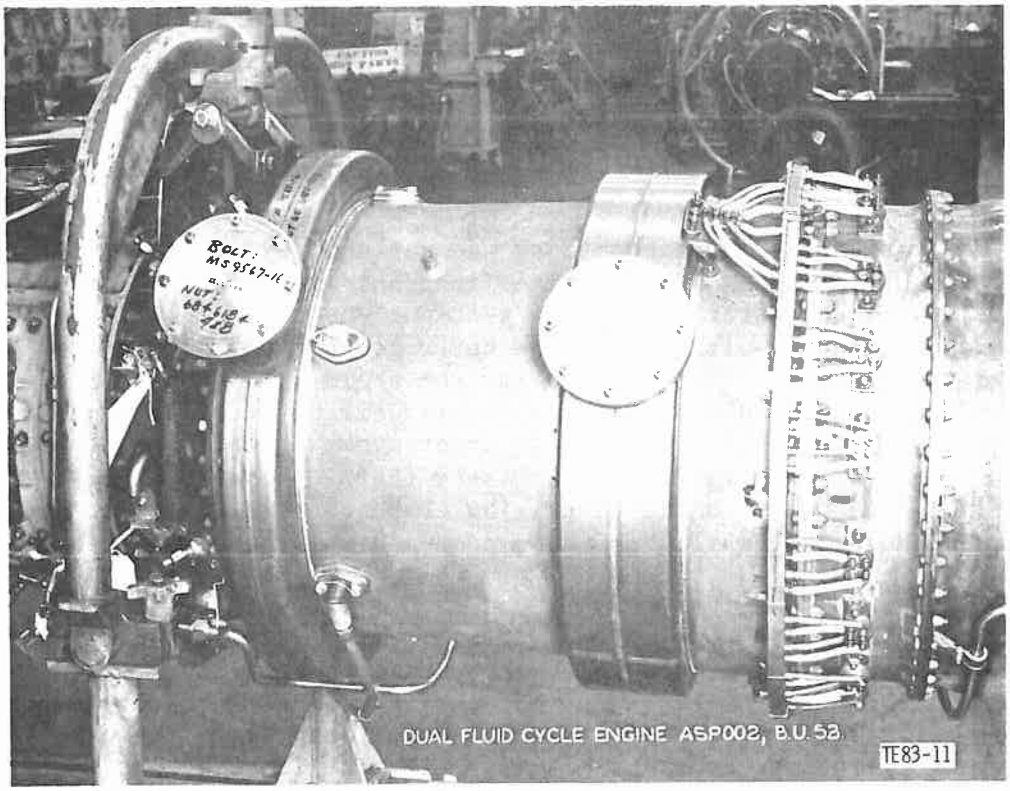

Figure 2. Engine with DFC outer combustion case installed.

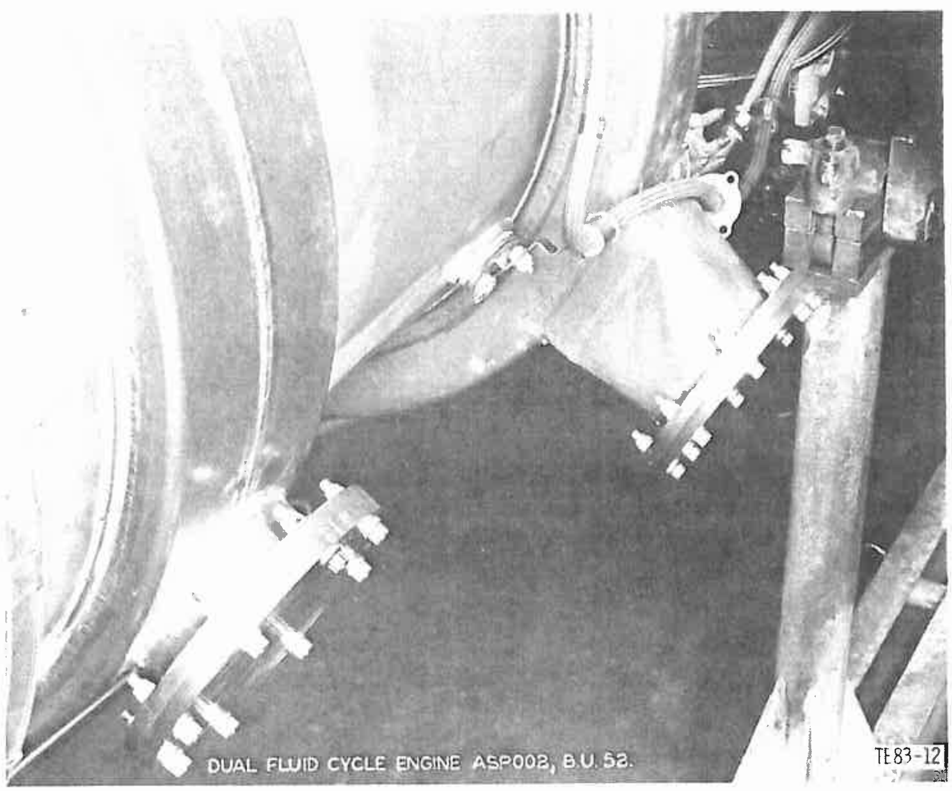

Figure 3. Steam inlet ports on the rear and front manifolds.

restore as much compressor performance as possible without refurbishing the compressor. The total time on the compressor was approximately 35,000 hr, much of which had been rigorous operation for various test programs.

SHAFTING AND BEARINGS

No special shafts were installed for the test. Although the increased power was expected to have an adverse effect on shaft life, the standard shafts were considered satisfactory because of the short duration of the test. A new rotor thrust bearing of the standard part number was installed for the test. Earlier preliminary studies of the effect of the steam flow had indicated the possibility of a reduction in bearing life. This, plus the uncertainty of life consumed of the old bearing during prior testing and use, prompted the installation of the new bearing to reduce the risk of bearing failure.

TURBINE SECTION

No special turbine parts were installed for the test. The turbine unit had been refurbished for a 1000-hr endurance test that immediately preceded the DFC testing. This had included the replacement of all first- and second-stage blades and vanes with new parts of the standard configurations. Nothing was done to obtain turbine flow areas other than those that resulted from the use of current production parts.

FUEL SYSTEM

The fuel system included standard fuel nozzles for liquid fuel, a standard fuel manifold, and a standard fuel pump. The capacity of the fuel system was not increased for this test.

ROTOR THRUST BALANCE SYSTEM

Although preliminary analyses had indicated that the rotor thrust loads might be altered by the effect of the steam injection, no changes were made to the thrust balance system for the test. Later studies indicated that the effects of the steam would not be as severe as initially estimated.

Test Facilities and Equipment

The test was conducted at the DDA Research and Engineering Center (Plant 8), Indianapolis, Indiana.

TEST FACILITIES

The test was conducted in Test Cell No. 871, which had been specifically adapted for this test by the addition of a steam supply, measurement, and control system. The decision had been made earlier to obtain steam from the plant steam system rather than from a waste heat boiler because of the extensive modifications to the test cell that would have been required to install the boiler. The system that had been installed had the capability of supplying 250 $lb/in.^2$ steam at flow rates up to 5.5 lb/sec.

Provisions were included to deliver steam to the engine front manifold, the rear manifold, and to both manifolds. The system provided for controlling and measuring the steam flow to each manifold. The design of the supply system to the manifolds ensured an equal flow to the two manifold entry ports, 180 degrees apart. The supply system also included a bellows section at each connection to the engine so that no loads would be transmitted to the engine outer combustion case. One connection to each manifold is shown in Figure 4. The steam flow rate was measured by the use of ASME-type orifices. Several sizes were used to cover the steam flow range with significant delta-P indication for accuracy.

The test cell standard equipment included lube oil and fuel supply systems for the engine as well as engine mounts, a reduction gearbox, and a means for measuring developed torque. The dynamometer of Test Cell No. 871 could absorb in excess of 7000 hp. The test cell standard equipment also included the means for measuring engine airflow, fuel flow, and various temperatures and pressures and the means for transmitting these measurements, plus speed and torque, to a computer center for recording and real-time performance calculations. The online performance calculations were displayed to the operator and test engineers for their use during the test. During this test, the calculation of steam flow to each manifold was also displayed for their use.

In addition to the test cell system for measuring developed torque, the test engine was equipped with an aircraft-type torquemeter shaft between the engine and the reduction gearbox. This provided redundancy during initial testing. During a high-turbine-temperature, high-steam-flow test condition, the yield strength of the shaft was exceeded and the shaft took a permanent set. Redundant torque measurements were not obtained after that.

The test cell was connected to an air facility capable of supplying engine air at a desired engine inlet temperature and pressure over the full operating range.

The installed engine ready for test with all instrumentation connected is shown in Figures 5 and 6.

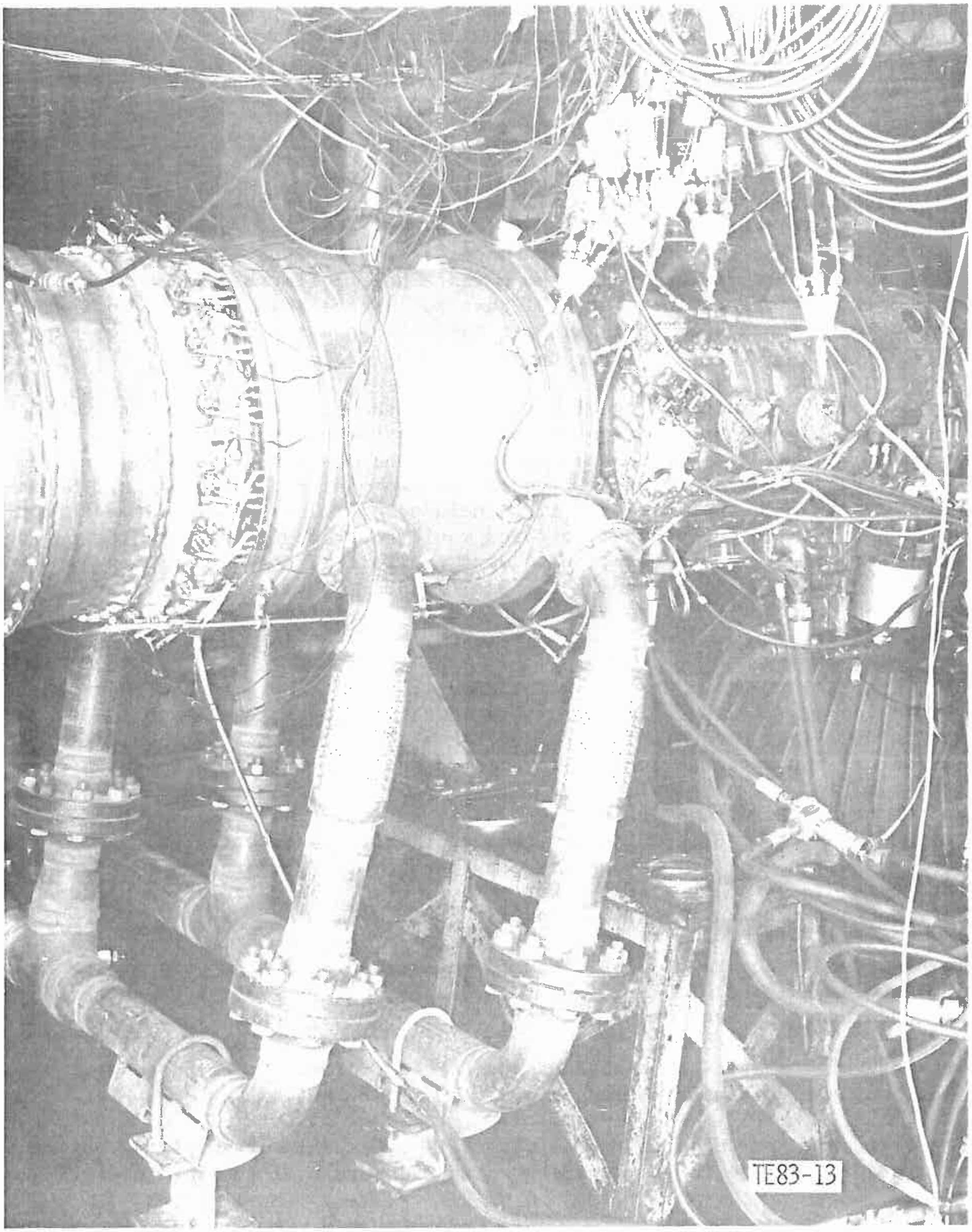

Figure 4. Steam connections to the DFC engine manifolds.

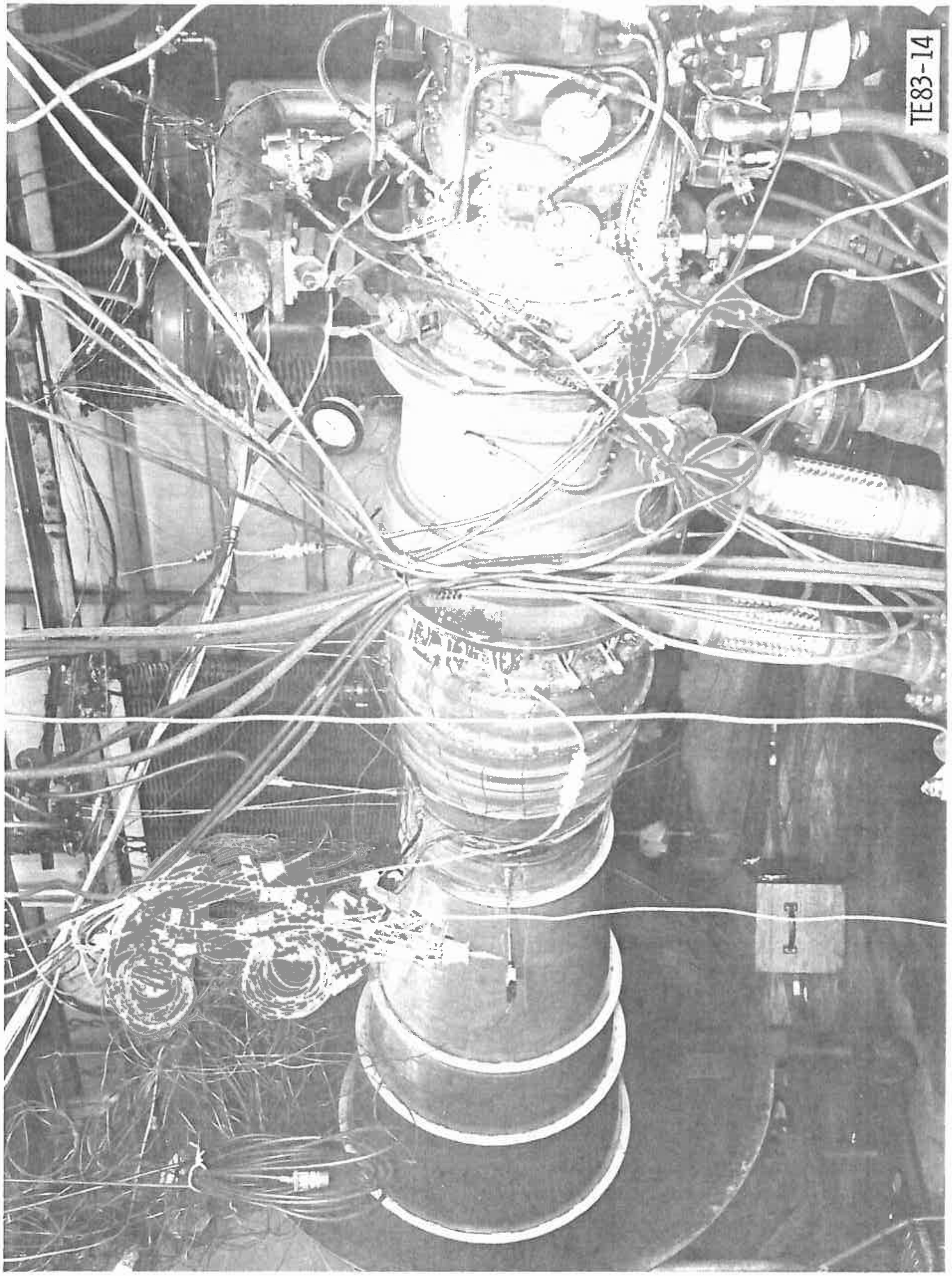

Figure 5. Installed DFC 501-KB test engine.

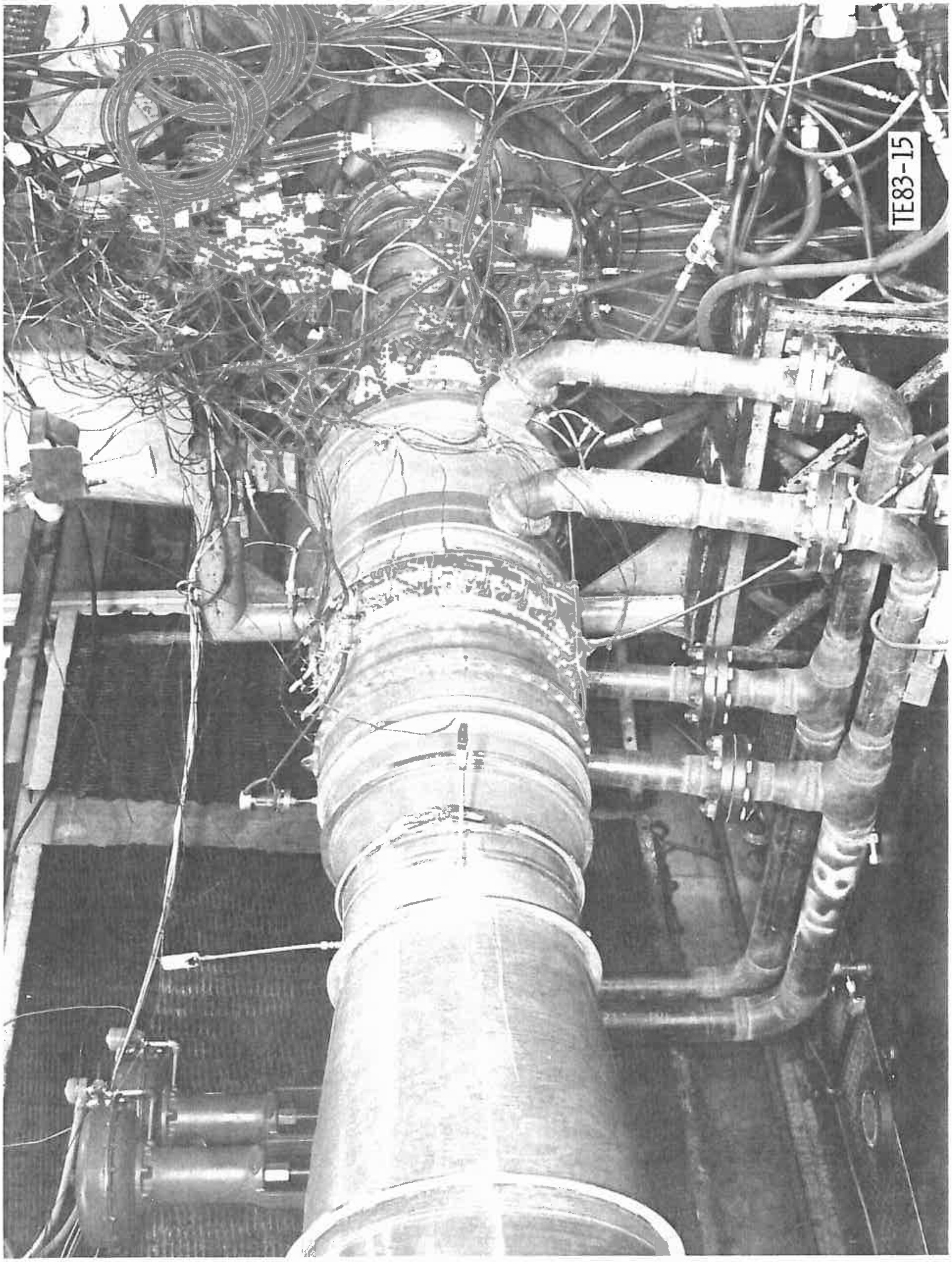

Figure 6. Installed DFC 501-KB test engine.

SPECIAL INSTRUMENTATION

Production Model 501-KB engines are equipped with 18 sampling turbine inlet thermocouples--three for the exit of each of the six combustors. To obtain an indication of any change in combustor outlet profile, the maximum temperature runs with and without steam were repeated with special turbine inlet thermocouples in three of the six combustors. These special probes had sensing elements at four depths.

At all test conditions instrumentation was installed to obtain the following:

- compressor discharge pressure
- compressor discharge temperature
- engine vibration at the compressor and the turbine
- limited survey of tailpipe exhaust gas temperature

During testing the engine was operated with an exhaust diffuser with 700 $in.^2$ exit area.

To provide an added degree of protection to the engine during this exploratory testing, a surge protection control was added. This control senses parameters and changes in these parameters that indicate impending surge of the compressor. When activated, the control closed fuel and steam valves and opened the regular compressor bleed valves plus additional 14th-stage bleeds added for this test.

Test Procedure

The engine was started in the usual manner without steam flow. The fuel flow was increased to the desired turbine inlet temperature. The steam flow to the preselected manifold(s) was initiated, and both the fuel and steam flows were increased to maintain the turbine temperature and attain the desired steam flow. The inlet conditions and engine speed of 13,820 rpm were maintained at constant levels.

The planned test conditions were as follows with 59°F inlet air temperature at unity ram:

Total steam flow--lb/sec	Turbine inlet temps--°F
0.0	seven-point calibration to 2100
1.0	1500, 1600, 1700, 1800
2.3	1500, 1600, 1700, 1800
3.6	1600, 1700, 1800
5.0	1700, 1750, 1800

The test was conducted with the steam flows shown above (1) through the front manifold, (2) through the rear manifold, and (3) split equally between the front and rear manifolds. When steam flow was not intended through a given manifold, blank-off plates were installed to ensure that no flow nor leakage occurred.

Test Results

PERFORMANCE

Baseline Performance

Prior to operation with steam injection, a seven-point performance calibration was performed to define the performance of the engine. The baseline performance test results showed that the test engine was lower in output power (shaft horsepower) and higher in specific fuel consumption (sfc) than is typical for the Model 501-KB production engines. This lower performance was attributed to two factors. First, the compressor performance was lower than expected. The compressor airflow and pressure ratio were lower than expected. This was attributed to extensive rigorous testing over significant operating hours prior to this test. The other factor was the relationship between the indicated turbine inlet temperature (TIT) based on the average of the 18 standard thermocouples (T/C) and a computed turbine inlet temperature (or burner outlet temperature [BOT]) based on fuel/air (F/A) ratio. The Model 501-KB engines, as well as other models of the Model 501/T56 family consistently exhibit a delta-T of -50°F (at 1800°F), where delta-T is defined as ($TIT_{T/C}$ - $BOT_{F/A}$). However, the test engine baseline performance testing indicated a delta-T of +30°F. The result was that the engine was actually operating 80°F cooler than a typical engine for a given indicated value. The airflow/pressure characteristics of this compressor may have had an influence on delta-T. The test engine observed shaft horsepower characteristics are shown in Figure 7. Also shown is the shaft horsepower performance curve adjusted for typical Model 501 engine delta-T. This same adjustment was made to DFC performance. However no adjustment was made for delta-T shifts unique to DFC operation. In addition to the baseline shaft horsepower curve, there is a relationship between turbine inlet temperature and shaft horsepower in typical production engines. Figure 8 shows the corresponding baseline thermal efficiency characteristic.

Dual Fluid Cycle Performance

When the engine was operated as a DFC engine the delta-T became more positive, i.e., computed F/A BOT decreased with respect to the indicated T/C TIT. The shift in delta-T with respect to the baseline characteristic is shown in Table I.

For purposes of this analysis the assumption was made that the above shift would occur with a typical production Model 501-KB operating as a DFC engine. The DFC performance values are presented on this basis. The validity of this assumption can be confirmed with DFC operation of a typical production engine.

The DFC performance characteristics presented in this report are based on (1) the test engine characteristics, (2) operation with liquid fuel, and (3) use of saturated steam.

Additional testing is planned to further define and refine performance characteristics. However, the purpose of the test was to obtain preliminary performance data, determine if unsuspected problems existed with DFC operation, select an injection location for the steam, and define operating characteristics that require more extensive exploration.

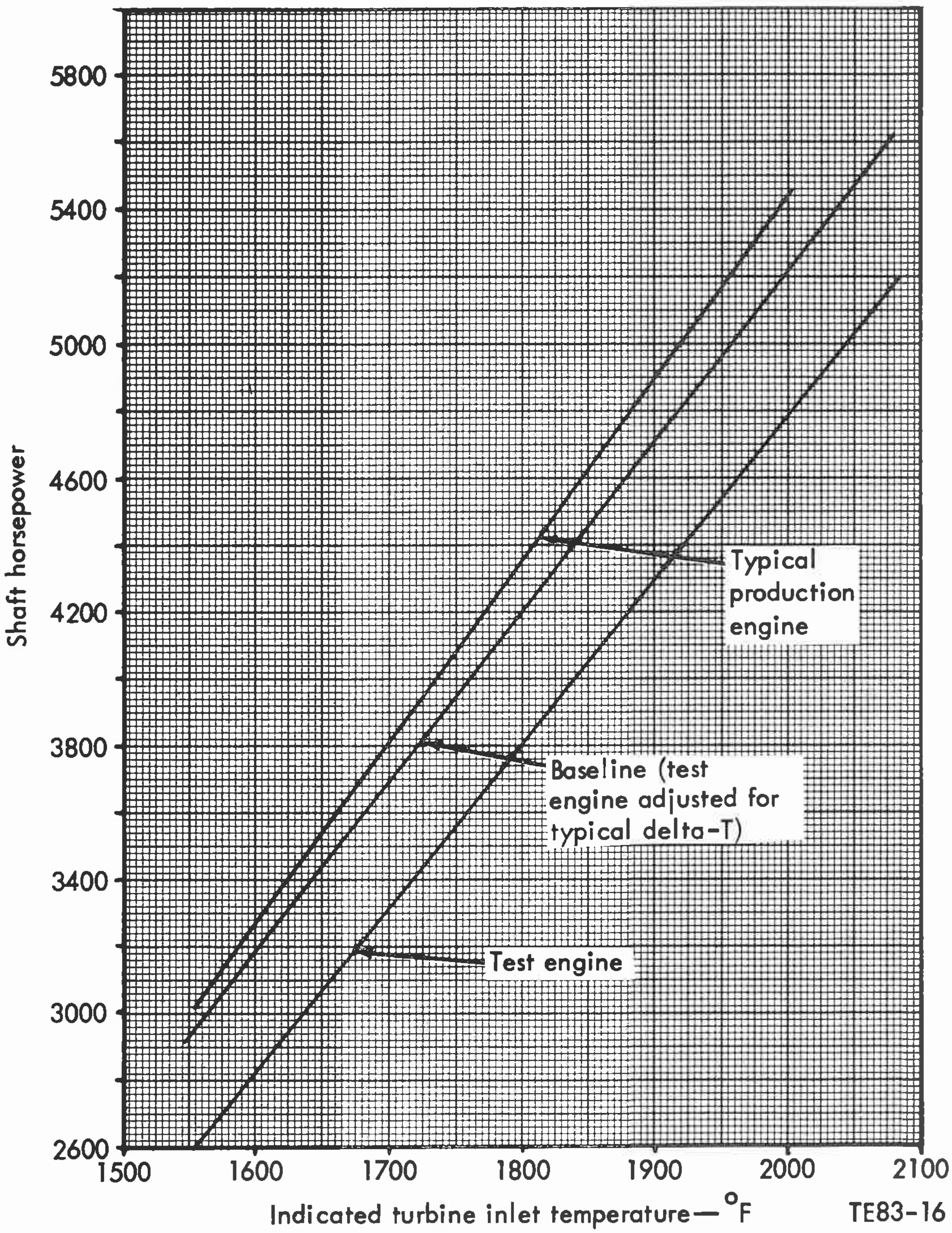

Figure 7. Shaft horsepower characteristics of test engine compared with typical production engine.

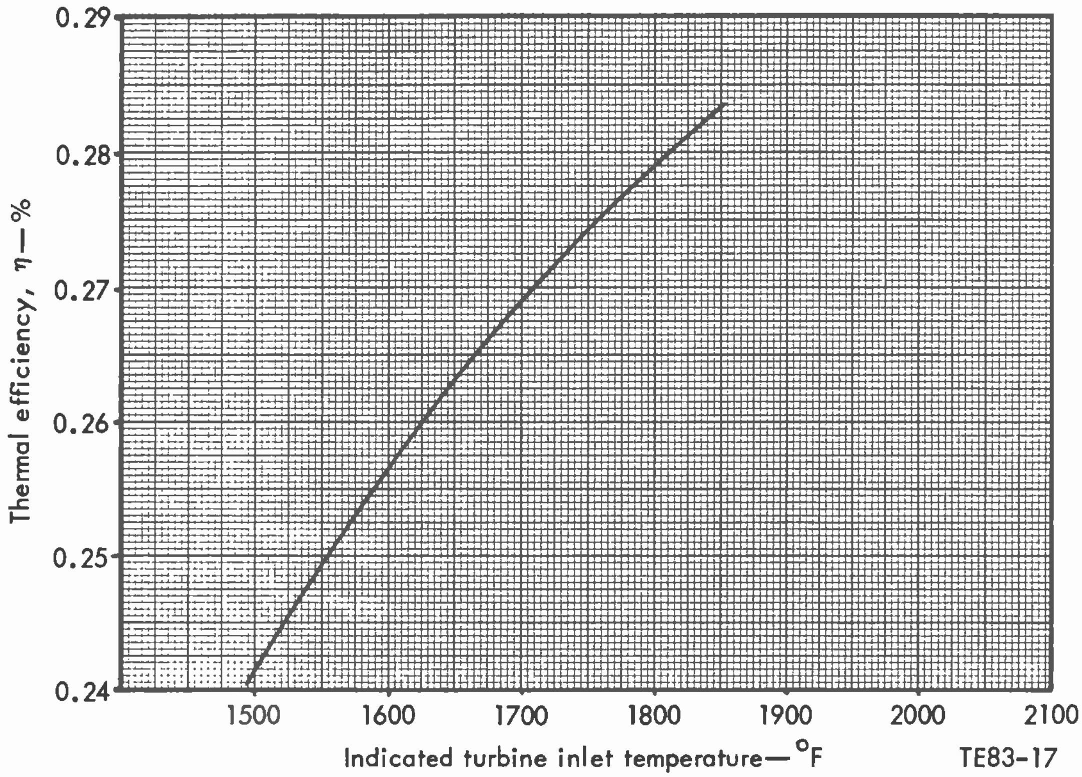

Figure 8. Baseline thermal efficiency characteristics.

Table I.
Effect of steam flow on delta-T.

Steam injection location	Increase in delta-T with various steam flow rates--°F		
	2.2 lb/sec	3.6 lb/sec	5.0 lb/sec
Front	30	30	30
Rear	40	70	90
Front and rear	15	40	50

The analysis of the DFC performance was done on the basis of computed BOT values for the test engine. Because the engine model specification and all performance monitoring by the customer are based on indicated TIT, the improvements in shaft horsepower and specific fuel consumption are presented in terms of indicated turbine temperature adjusted for typical baseline engine delta-T. The reason for the varying delta-T values with varying steam flows and injection locations is reserved for future testing to help resolve as is the proper method of accounting for the shift if it should also occur in a DFC version of a typical production Model 501-KB engine.

The shaft horsepower characteristics of the test engine with varying steam flow rates and injection locations are shown in Figure 9. The test results

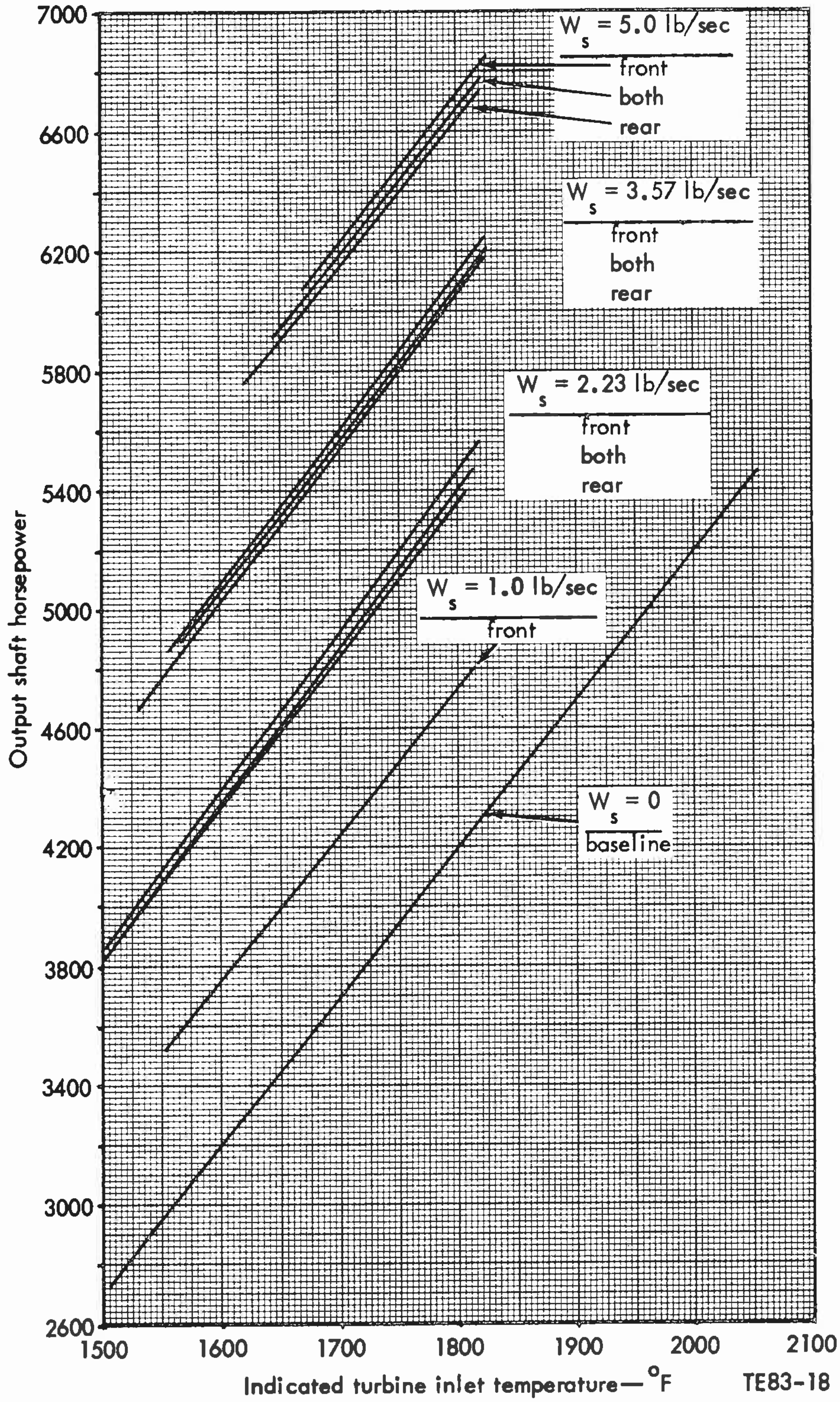

Figure 9. Shaft horsepower characteristics of DFC test engine.

indicated a generally uniform increase in shaft horsepower with increasing steam flow except for the 5.0 lb/sec steam flow rate conditions. With steam flows of 5.0 lb/sec, the shaft horsepower did not increase with increased TIT at the same rate as shaft horsepower increased at the lower steam flow rates. The reason for the lower rate of increase of shaft horsepower is not known based on the data from this initial test. In terms of shaft horsepower, the injection of steam through the front manifold was slightly better than through both manifolds. Injection through the rear manifold consistently produced the lowest shaft horsepower improvement.

The thermal efficiency characteristics demonstrated by the test engine are shown in Figure 10. Over the range of turbine temperatures tested, the thermal efficiency was near constant with steam flows of 5.0 lb/sec divided between both manifolds. The thermal efficiency was consistently higher with the steam injected through both manifolds for all steam flow rates. The thermal efficiency calculations took into account that the steam was not superheated to the degree expected for an operational installation.

The maximum thermal efficiency attained with the test engine was less than expected. The following factors may have influenced this result.

<u>Compressor Condition</u>

With the lower than normal airflow and pressure ratio characteristics of the compressor, the higher steam flows may have had a greater effect than prior analytical studies would have indicated.

<u>Combustion Efficiency</u>

Combustion efficiency was assumed to have remained constant. However, there were some indications, but no direct data, that combustion efficiency decreased at the higher fuel and steam flow conditions. The higher fuel flows were higher than would be expected in an operational installation because of the lower steam temperatures for the test.

COMBUSTOR OUTLET TEMPERATURE PATTERNS

A combustor outlet temperature survey was conducted during the test to determine if hot spots existed in the temperature profile that would shorten turbine life. As discussed in the special instrumentation section, three combustor positions were instrumented with four-element probes. These three represented the varying steam flow conditions related to one of the manifold supply ports. The other three would be expected to yield similar results. Figures 11, 12, and 13 show the temperature distribution of each combustor outlet. Each group of three values is for 5.0, 3.6, and 0.0 lb/sec steam flow. The resultant turbine airfoil tip-to-root temperature gradient at the combustor exit is shown in Figure 14. The profiles are essentially the same. The standard deviation of the temperatures measured at each level ranged from 256°F (maximum) to 105°F (minimum) for 5.0 lb/sec, from 254°F to 98°F for 3.6 lb/sec, and from 217°F to 73°F for 0.0 lb/sec. The overall standard deviations for each steam flow rate were 228°F for 5.0 lb/sec W_s, 216°F for 3.6 lb/sec W_s, and 196°F for 0.0 lb/sec W_s.

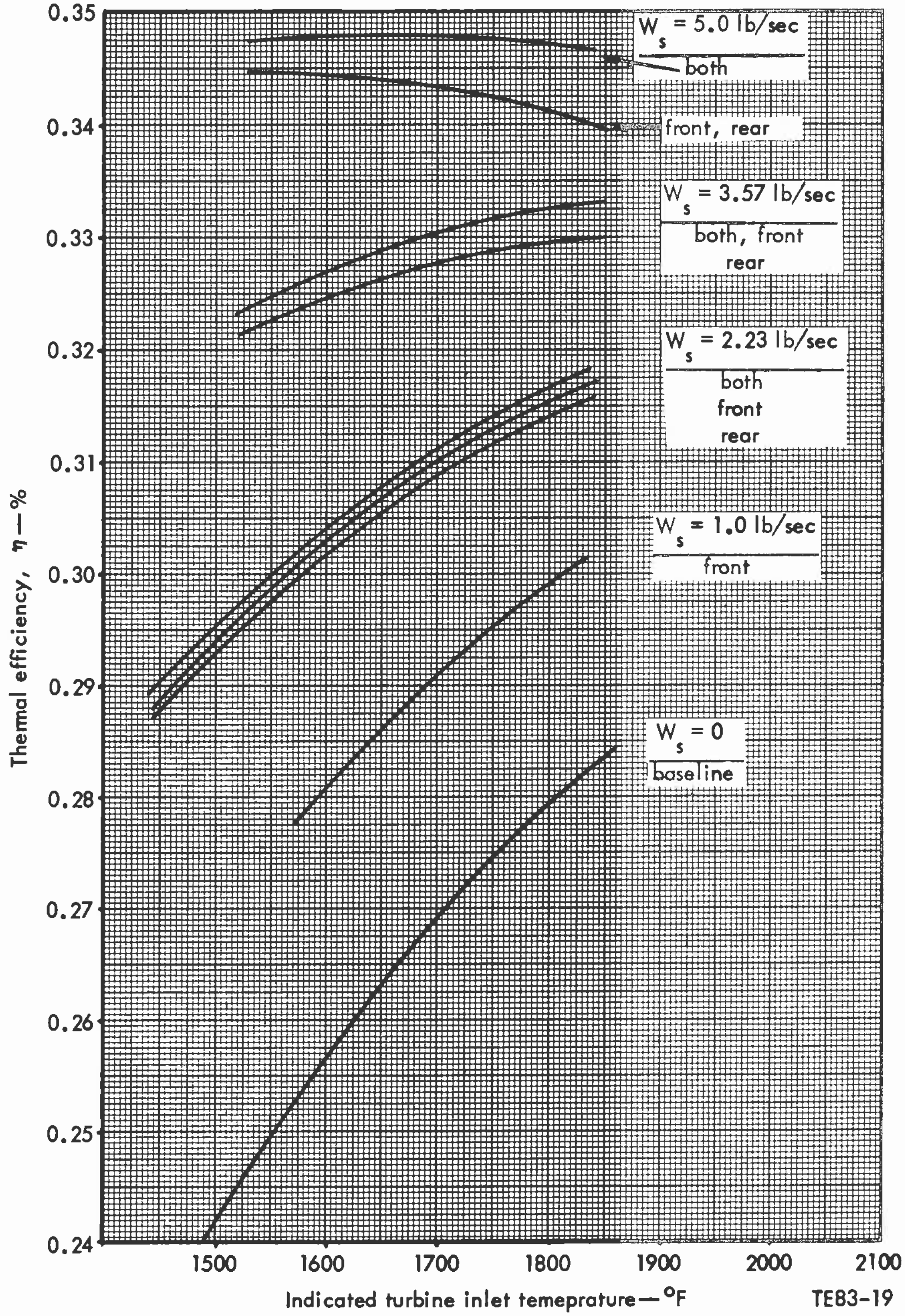

Figure 10. Thermal efficiency characteristics of the DFC test engine.

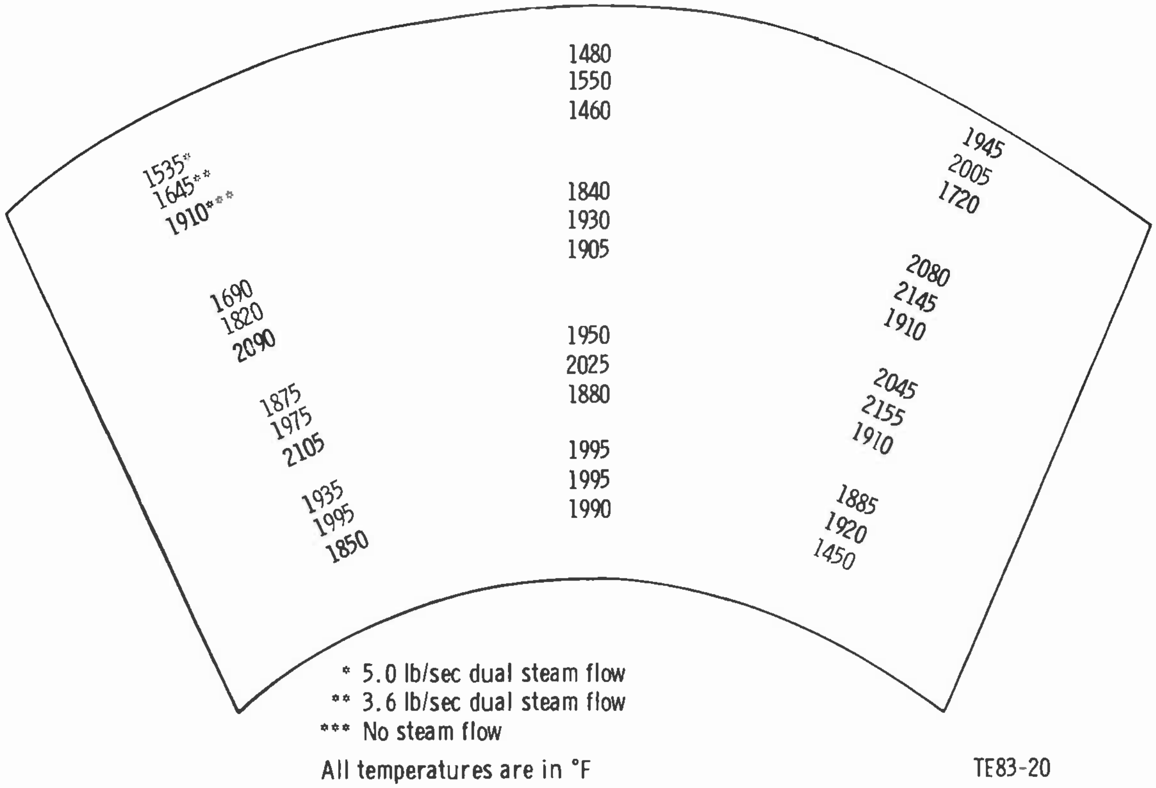

Figure 11. Combustor No. 1 outlet temperature pattern.

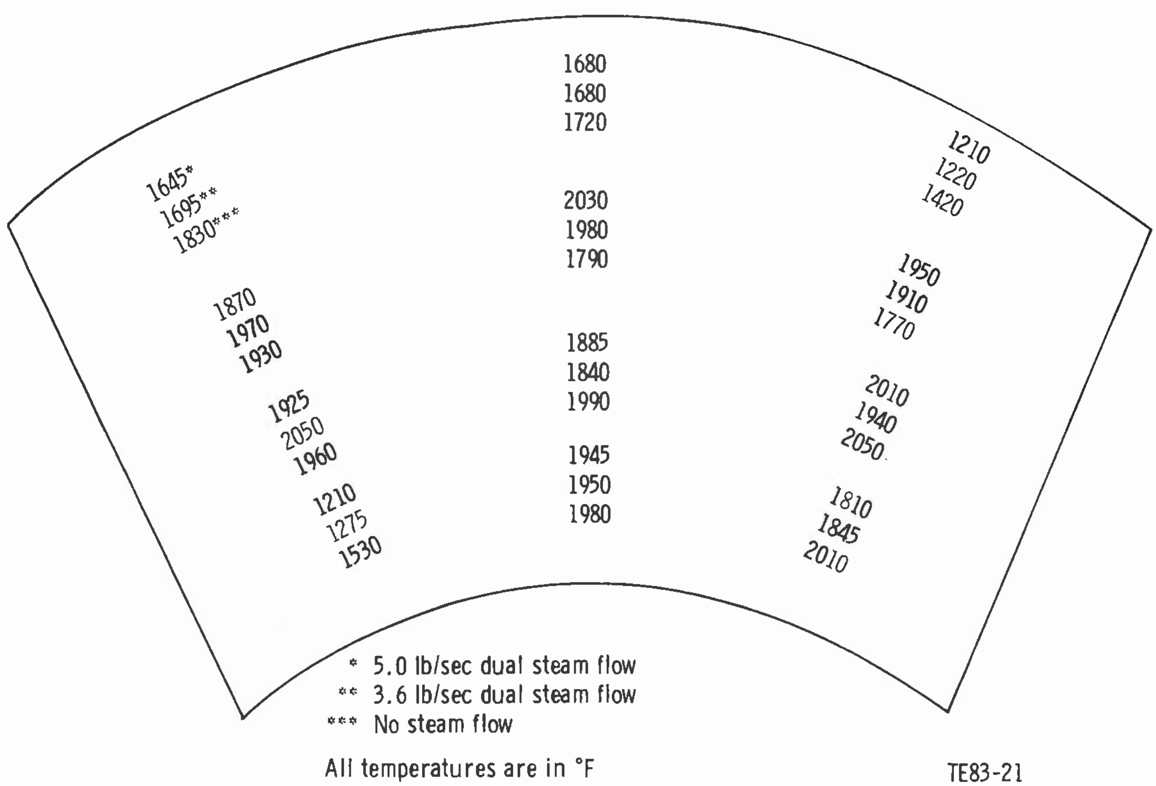

Figure 12. Combustor No. 2 outlet temperature pattern.

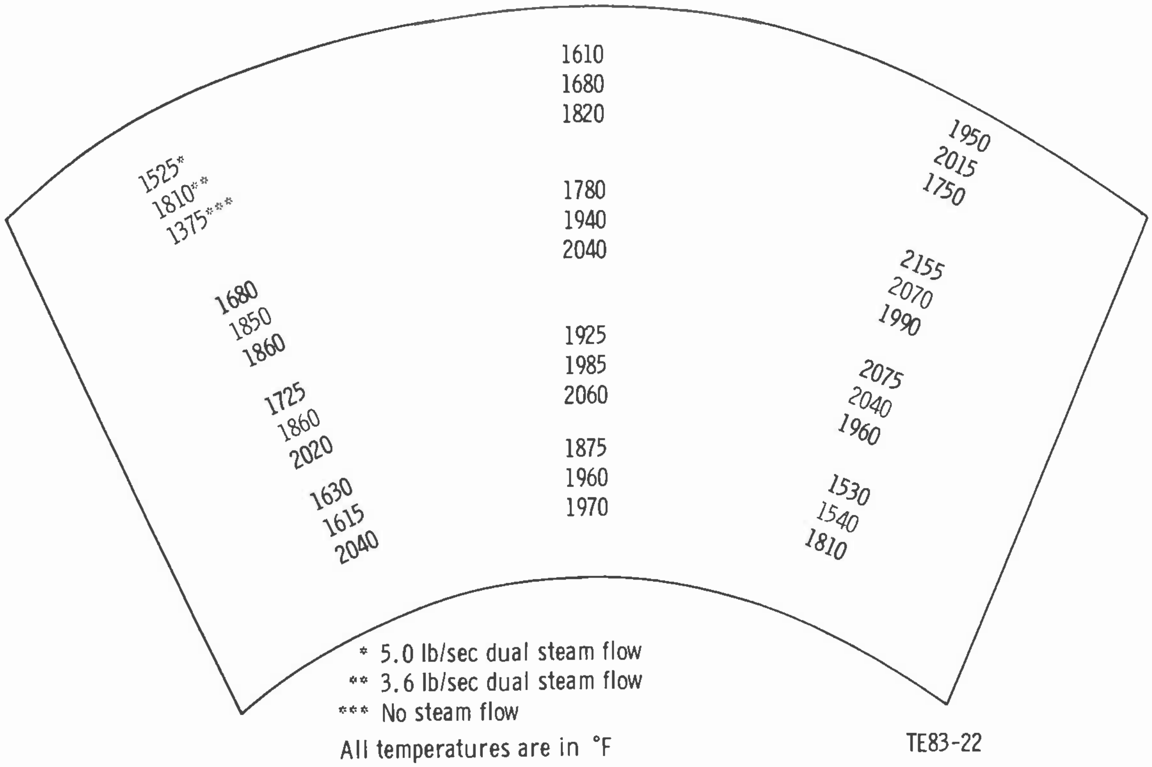

Figure 13. Combustor No. 3 outlet temperature pattern.

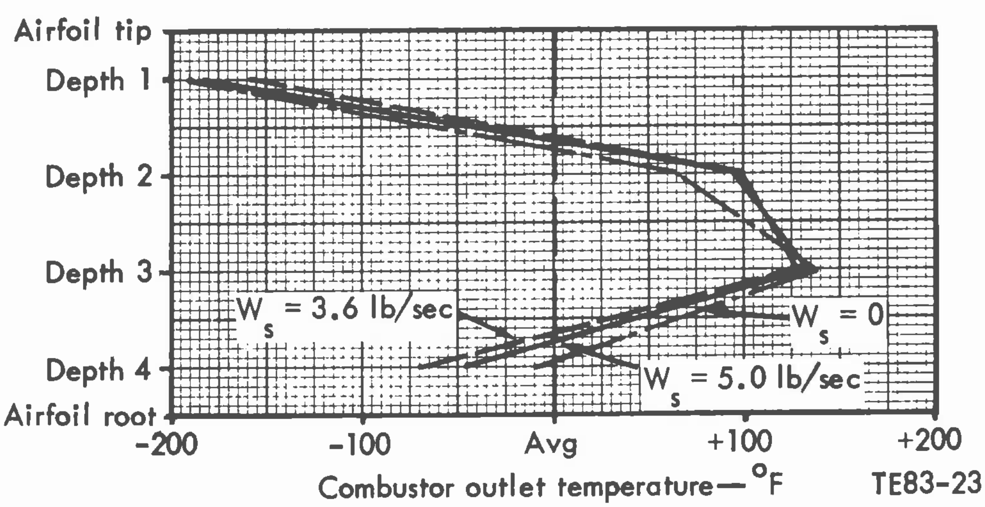

Figure 14. Combustor outlet tip-to-root profile for 1800°F turbine inlet temperature.

From these results, the injection of the steam into the combustors through the dual manifolds had only a slight effect on the temperature profile and therefore should have little effect on turbine life.

ENGINE OPERATION

The engine operated in a satisfactory manner as a DFC engine.

The low surge pressure ratio of the test engine compressor (10.5:1) compared with that of a typical production engine (>13.0:1) required special care during transient operation so that surge would be avoided. During one high-temperature test condition when attempting 5.5 lb/sec steam flow, the surge protection system shut down the engine. This was the same condition that yielded the torquemeter shaft. In a production DFC engine, a compressor would not be expected to have as low a surge margin as this test engine. The shafting for a DFC engine will be designed for considerably higher torque capacity than available for the test engine.

During low turbine temperature operation, e.g., 1400°F, and hence low fuel flows, inadvertent high steam flows generally extinguished the combustion process. During steady-state operation of a field DFC engine with a waste heat boiler, this would not be a problem because steam generation and turbine temperature are related. This was not so with the DFC test. However, a field installation engine could encounter the same conditions as the test engine following a sudden and substantial reduction in load, which would reduce engine fuel flow much faster than steam flow. A suitable control system could take this situation into account.

Field installations of gas turbine engines require clean air inlet systems, free of debris, which could, if present, damage the compressor. A DFC engine installation will also require that the total steam supply system be free of debris including pipe scale. This was underscored during the test and at the post-test inspection when evidence showed that scale and weld slag had been carried by the steam into the turbine. High steam rates had been flowed prior to the test to clean the piping.

POST-TEST CONDITIONS

A post-test performance calibration was conducted at the conclusion of the DFC testing. No deterioration in performance occurred from the pretest performance calibration.

During engine disassembly inspection following the test there was no evidence of any adverse effects of the steam. Figures 15, 16, and 17 show the condition of a fuel nozzle, a turbine vane segment, and a combustor. The condition of these was representative of the condition of the other parts.

No adverse effect was noted on the lubrication system including air/oil labyrinth seals during or following the approximate 16 hr of operation with steam. During DFC operation, these seals are exposed to a mixture of air and steam.

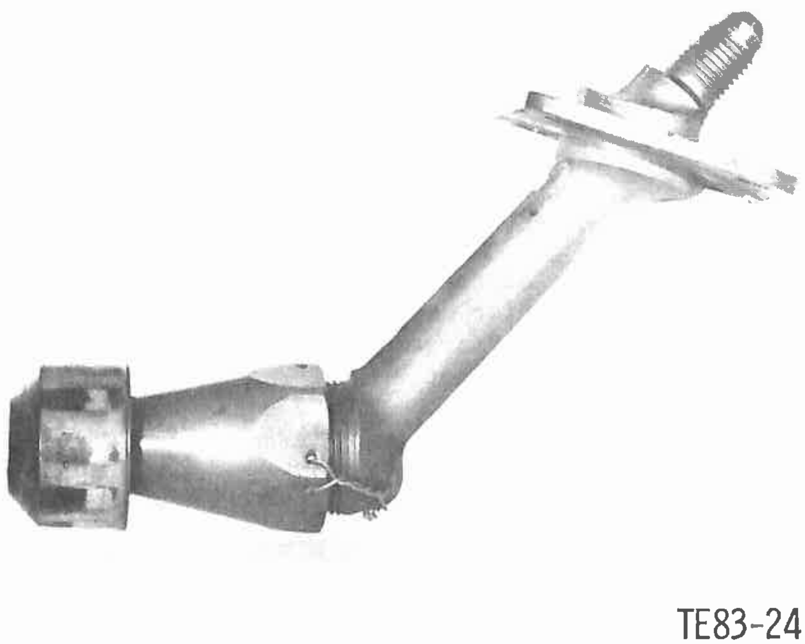

Figure 15. Fuel nozzle following DFC testing.

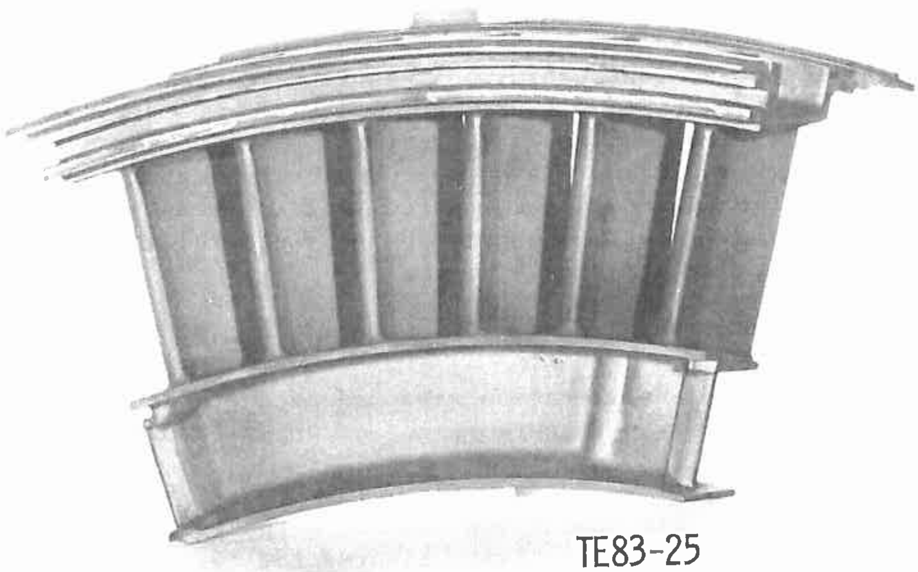

Figure 16. Turbine vane segment following DFC testing.

Figure 17. Combustor following DFC testing.

There was one adverse effect of the facility modification. Beads of iron from the welding of the new steam pipe were carried into the turbine, causing some blade surface damage even though steam had been flowed to clean the piping. Spectrographic analysis confirmed that the material was essentially pure iron and did not come from any engine part. This underscores the need to thoroughly clean a steam supply system as well as an air inlet system.