DESIGN, PERFORMANCE AND OPERATIONAL CHARACTERISTICS OF A 6500 HORSEPOWER HIGH PERFORMANCE INDUSTRIAL GAS TURBINE

by

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ABSTRACT

This paper will describe the 570-K high performance industrial gas turbine and provide technical rationale for the design approach and performance limits. Construction details are discussed, including assembly of major modular components. The combustion system is explained, as are the mainshafting and bearings, the lube system, seals and vents.

In addition, the engine torquesensor, speed and temperature sensors are discussed along with the electronic control system. Finally, the 570-K production program is identified.

INTRODUCTION

The 570-K industrial gas turbine is a 6445 horsepower engine which received serious attention during the 1974 energy boycott because of its attractive efficiency. The engine received its original design impetus in 1970 which resulted in a demonstrator engine in 1971. By 1975 fifteen engines were manufactured and nearly 2500 hours of intensive testing were accumulated.

In 1975 it seemed apparent that industry demanded greater turbine efficiency and reliability, and a 6000 to 7000 horsepower turbine would fill a gap in the turbine horsepower spectrum. A market study was conducted which confirmed our estimates. The goal was to make maximum use of the technology already substantiated by test, to modify performance limits to ensure high reliability, simple maintenance and long life, and to modify materials in the interest of good maintainability and lower use of strategic materials without compromising reliability. In gas industry service, the engine was to have a major repair interval of 30,000 hours or more.

DESIGN CONCEPT

Industrial gas turbines are most often applied in continuous duty service where high availability and minimum downtime are essential. Fuel cost will also become an increasingly important factor so that design priorities must consider the following:

A. High Availability — Operational interruptions are far more costly than any offsetting equipment cost savings.

B. Ease of Maintenance — Mechanical equipment must be maintained. Ease of diagnosis, speedy repair and/or modular replacement on-site improve availability.

C. Fuel Efficiency — After A and B are established, fuel cost can be the next most important criterion since a turbine can easily consume in one year two times the first cost of an engine in fuel. Fuel can represent 90% to 95% of the total cost of turbine operation.

The 570-K incorporates the proven modern concepts developed from a variety of hardware oriented engineering programs conducted during the past 35 years and resulting in more than 60,000 engines. These features make the 570 one of the most up-to-date industrial turbines available (Figure 1). In particular, we wish to acknowledge the contributions of several major gas turbine programs:

- For its production advantages, the 570-K must acknowledge the significant production experience of the 501 turboshaft engine — twenty-five years in production and going strong with over 13,000 engines built and a current schedule of 40 per month.
- A high performance compressor, using technology gained as one of several contractors to the U.S. Air Force Conducting Advanced Turbine Engine Gas Generator (ATEGG) development.

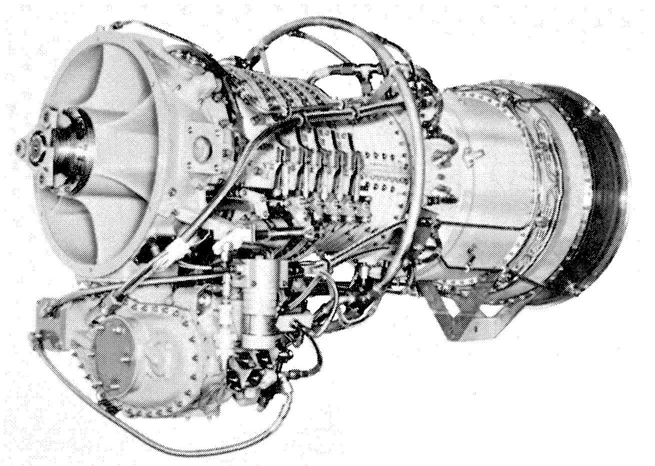

Figure 1. Model 570-KA Industrial and Marine Gas Turbine Engine.

- Advanced annular combustor cooling techniques, from the GMA 100, multi-year technology program, resulting in low cost film cooling and long combustor life.
- Efficient air cooled turbine vanes and blades, a technique in its twentieth year of development by Detroit Diesel Allison now in use on virtually all high efficiency turbines as a means of assuring modest turbine blade temperature for extended life.

Material selections and allowable design stress levels were influenced by minimum material properties, machining induced internal stresses, parts dimensional tolerances, performance variation, extremes of ambient conditions and the most adverse dimensional stack.

ENGINE PERFORMANCE

The basic gas turbine design from which the 570-K engine was adapted required a power output of 8079 horsepower at turbine metal temperatures considered to be risky for long engine life with present day turbine alloys and cooling techniques. A major technical decision was to limit turbine metal temperatures to that of the 501-K industrial gas turbine to benefit from the extensive successful experience on that engine with extended repair intervals.

Engine performance is plotted in Figure 2. The I.S.O. rating for continuous duty is 6445 horsepower at 11,500 RPM and a heat rate of 8473 Btu (LHV) horsepower-hour. A study of the performance data reveals the especially attractive heat rate, even at part load where turbines usually suffer a substantial loss in efficiency. Figure 3 further identifies a comparison of engine heat rate with a typical industrial gas turbine at either constant RPM or power varying with the cube of power turbine speed. Constant RPM would characterize a prime mover for an electric set, while cube law power would represent compressor or pump operation.

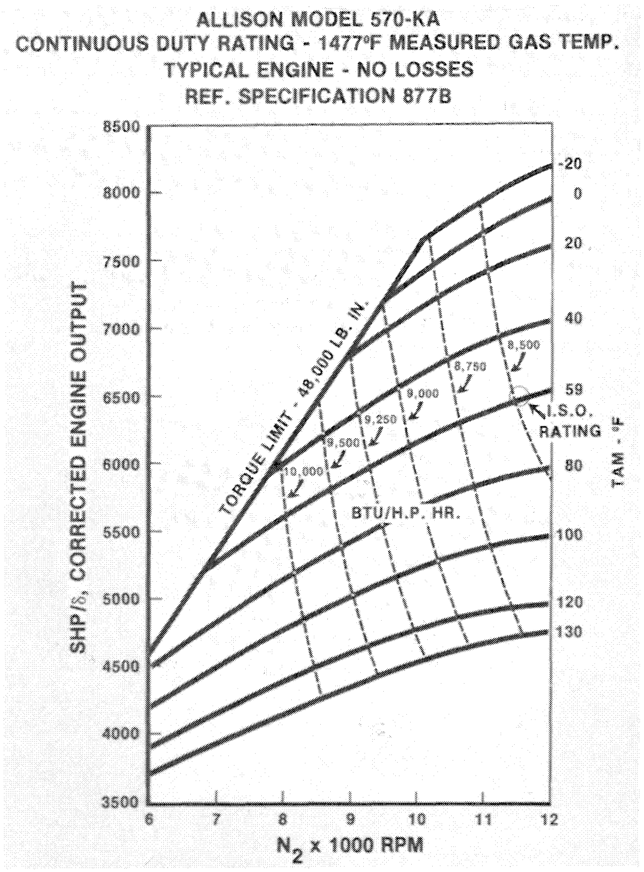

Figure 2. Estimated Performance.

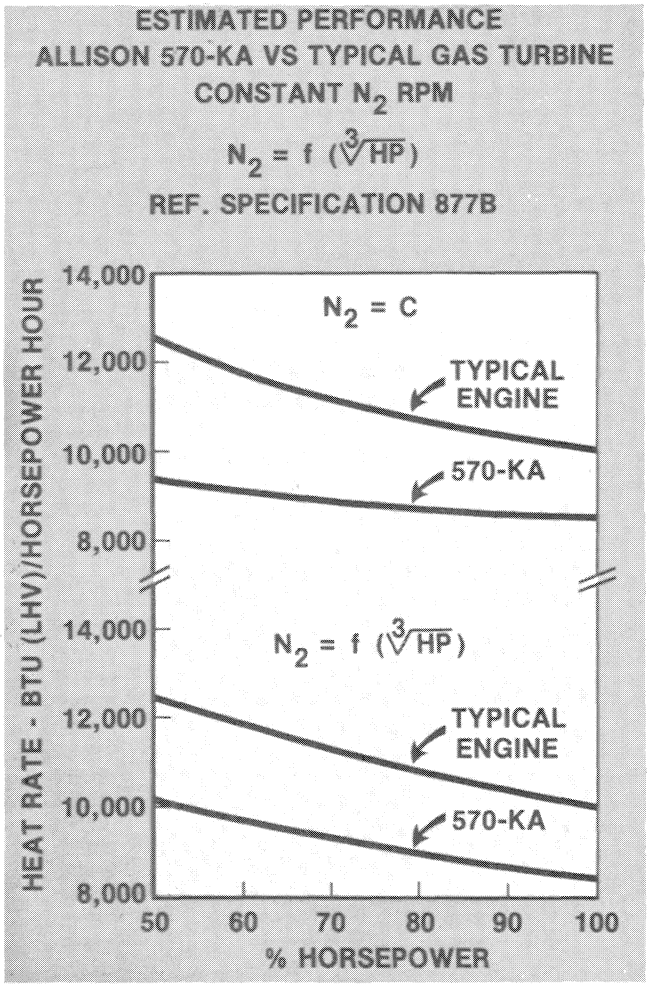

Figure 3. Power and Heat Rate Curves for the 570-KA Engine.

DESCRIPTION OF THE ENGINE

The model 570-KA industrial gas turbine, shown in Figure 4, is a front-drive, free-turbine engine with an output shaft speed up to 12,000 RPM. It incorporates variable geometry in the compressor, an annular combustor, air-cooled turbine blades and vanes, and a power turbine designed to provide high efficiency over a wide range of output power. The general mechanical arrangement is shown in Figure 5. Note the modular construction, a characteristic of all DDA turbine products, that simplifies and speeds up field repair or replacement.

COMPRESSOR

The compressor consists of the air inlet and accessory drive assembly, compressor rotor, and case and vane assembly. The air inlet housing is an aluminum casting designed to provide the forward structural support for the engine, support the front bearings for the gas generator and power turbine shafts, house the torquesensor and inlet guide vanes and support the accessory gearbox, lube pumps and starter.

The compressor assembly is a variable geometry, 13-stage axial flow unit with pressure ratio of 12:1 and an airflow of 42

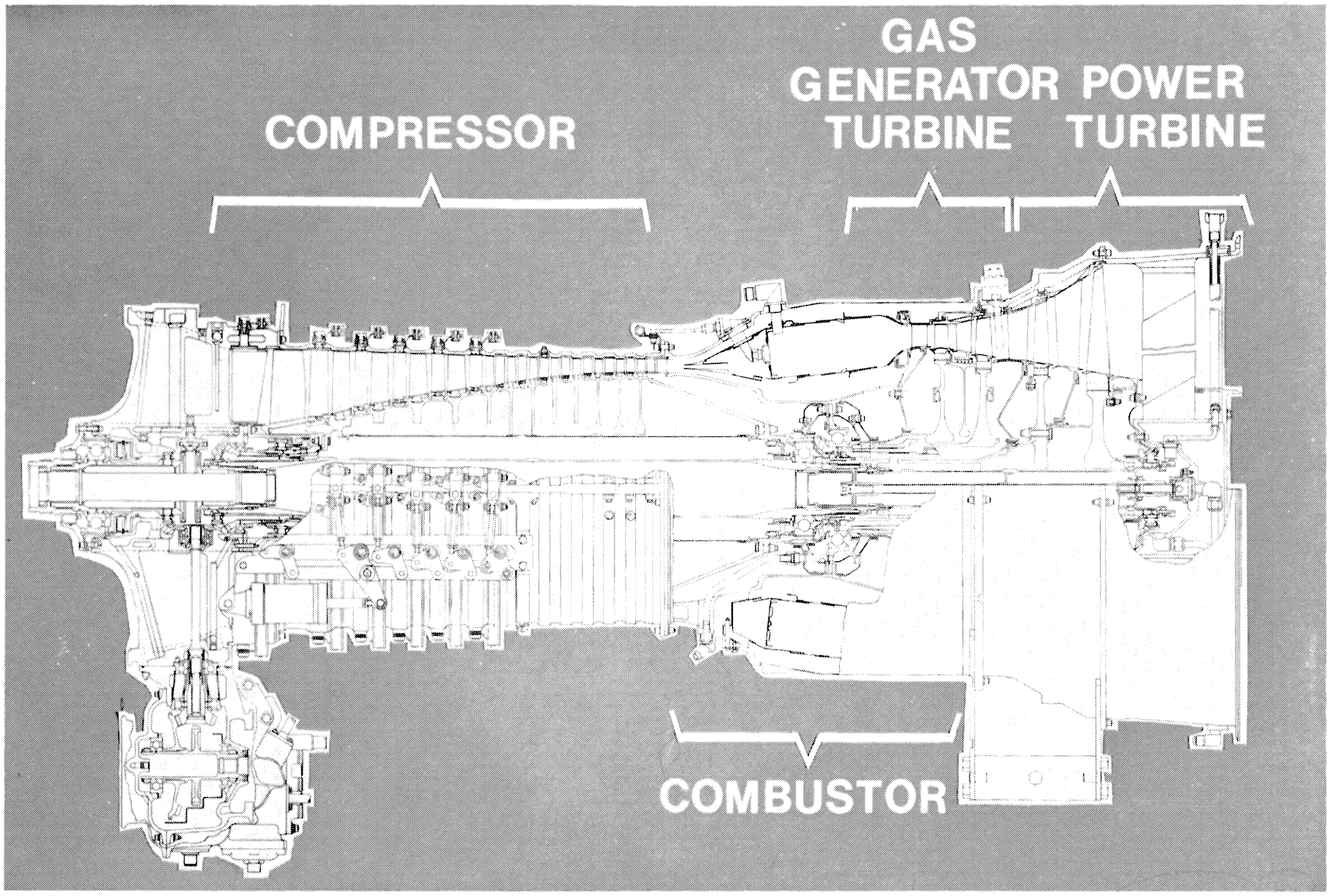

Figure 4. Engine General Arrangement.

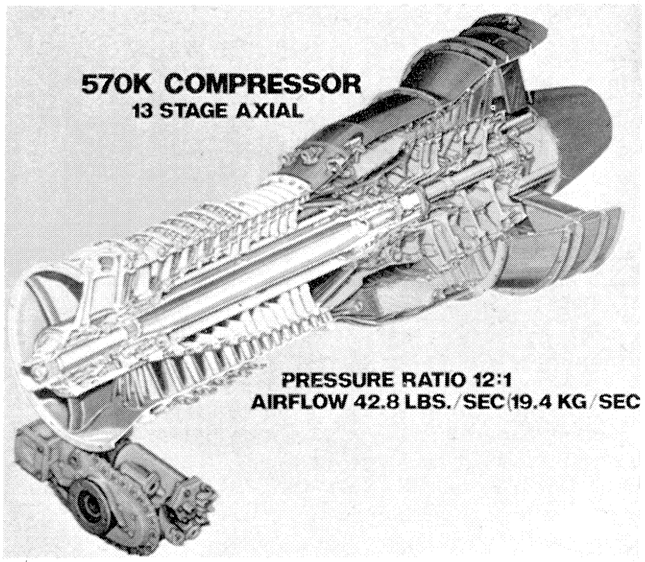

Figure 5. Cutaway of 570 K Gas Turbine Engine.

pounds of air/sec. It comprises a rotor with an integral welded drum and cone shaft with 12 stages of circumferential dovetail steel blades bolted to a first-stage wheel and axial dovetail blade assembly (see Figure 6). This construction makes for a rigid assembly unaffected by engine order excitation.

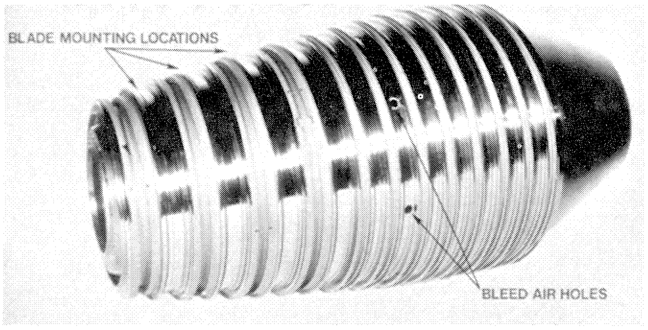

Figure 6. Compressor Drum.

The case assembly consists of a steel, horizontally split two-piece case, variable and fixed vanes and variable vane actuation system. The horizontally split case permits the compressor rotor to be assembled and balanced as a unit and avoids the stacking of individual wheels and stator vanes, eliminating the greater tolerances and performance losses associated with circumferential housings. A case half may be removed for inspection or repair of flowpath components. The inner surface adjacent to the blade tip path is sprayed with abradable aluminum to maintain close, uniform tip clearances. Stator vanes are supported with both inner and outer bands to eliminate vane flutter and fabricated into 180 degree ring assemblies. An abradable band is attached to the inner ring to act as an interstage seal (see Figure 7). In the unlikely event of a blade failure caused by a rotor overspeed condition, the case is designed to contain the failure.

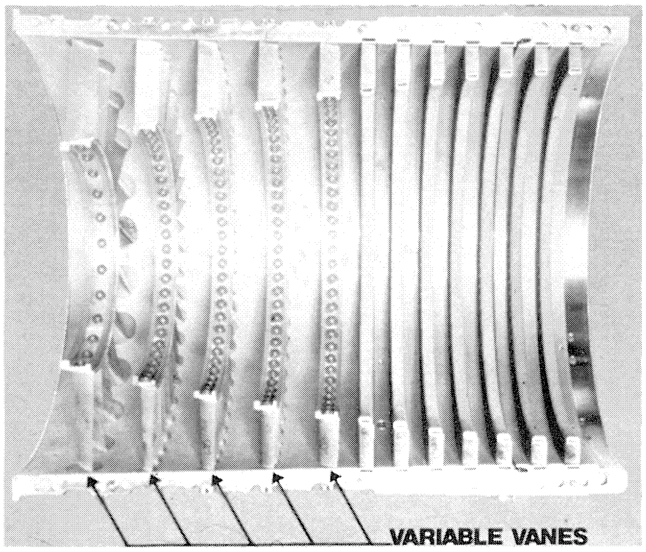

Figure 7. Upper Half of 570K Compressor Casing.

COMPRESSOR VARIABLE GEOMETRY

Outside the compressor case, individual levers are attached to the six rows of movable vane shafts and secured with self-locking cap screws. The lever arms are attached to 180 degree segmented actuating rings which encircle the compressor. Clevises are bolted to the ends of the ring segments to join the segments and to provide attachment points for the actuation linkage. Special attention was given to ensure the use of low friction, self-aligning bearings with low wear characteristics.

Actuation of the variable vanes is through a bell crank system. Two hydraulic cylinders operating from lube oil pressure (see Figure 8) supply the force to actuate the vanes. Interconnecting rods are used between the cylinders and the master bell cranks (inlet guide vanes). Tie bars connect the master bell cranks to the inlet guide vanes and to stages one through five of the compressor variable vanes.

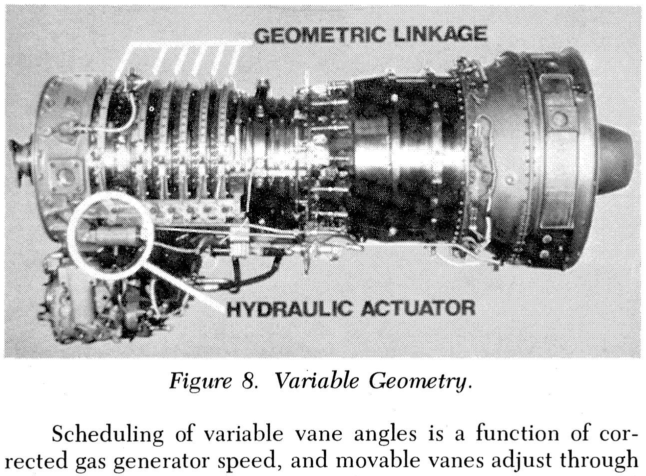

Figure 8. Variable Geometry.

Scheduling of variable vane angles is a function of corrected gas generator speed, and movable vanes adjust through angles of 40 to 60 degrees, depending upon compressor speed and output power required at a given ambient temperature.

Positioning is determined by the engine's electronic control unit from analog signals processed by the control.

ANNULAR COMBUSTOR

The 570-K combustion system incorporates a three-passage diffuser (Figure 9), 16 air spray fuel injectors, an annular combustion liner with high-intensity cooling and two low-tension gap type spark igniters. The basic design of the combustion system was directed toward high efficiency, low emissions and smokeless combustion at all operating conditions, uniform burner outlet temperature, high endurance life and low metal temperature. The diffuser is designed to precisely divide compressor discharge air (Figure 10) toward the various combustor liner zones to control temperature distribution and burner efficiency. To obtain the optimum combustor outlet temperature pattern, combustion liner cooling air must be kept to a minimum. Reduced cooling air requirements allows more air for temperature distribution control and greater power output at higher gas turbine efficiency.

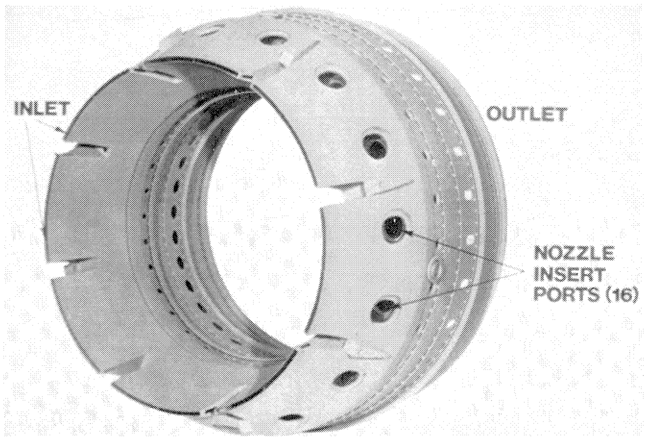

Figure 9. Annular Combustor.

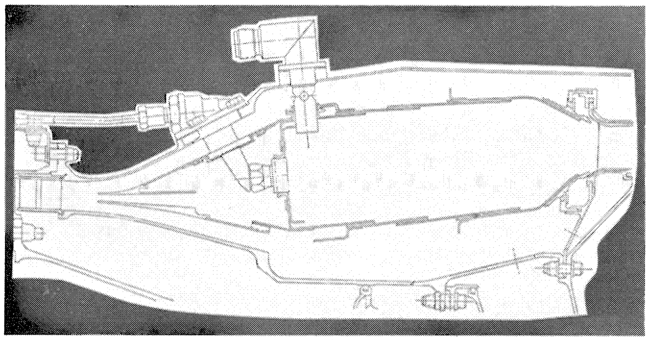

Figure 10. Combustor Cross Section.

Manufacture of the combustion liner is especially interesting in that the Hastalloy X details are prepared by having the holes for the primary and secondary air supply cut on a numerically controlled tape laser cutter rotatable automatically on three axes and manually on a fourth axis. Adjustments in hole pattern or hole shape may be accomplished readily by reprogramming the tape. Reproducibility of holes is extremely accurate.

FUEL INJECTORS

Sixteen fuel injectors were selected from an optimization study to determine the proper number of fuel injectors needed to maintain good combustor temperature distribution and low emission and smoke levels while ensuring good light-off characteristics under all starting modes.

GAS GENERATOR TURBINE

The gas generator turbine is a two-stage turbine splined, locked and overhung from the compressor rotor. The turbine is of a controlled vortex design selected to accomplish a desirable work distribution over the blade span and better efficiency than available from a free vortex design. Both stationary and rotating airfoils are investment cast and internally cooled by compressor air to control metal temperature to a desirable limit (see Figures 11 and 12). The second stage rotating airfoils are shrouded with knife edge tips to minimize air leakage and stationary foils are fitted securely to prevent leakage. Turbine cases are vertically split and designed to contain a blade failure.

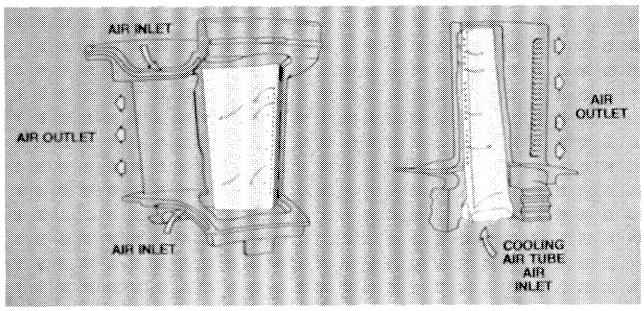

Figure 11. First Stage Turbine Vane and Blade Cooling.

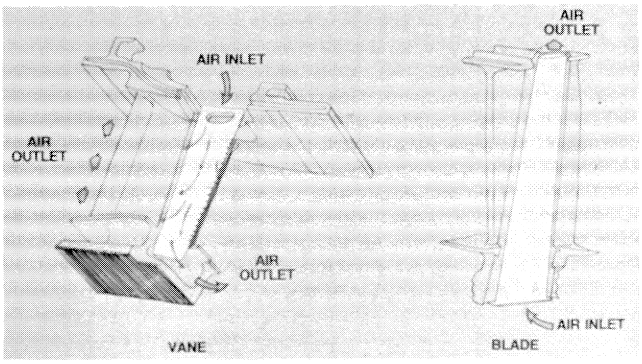

Figure 12. Second Stage Turbine Vane and Blade Cooling.

POWER TURBINE

The design and performance of the 570-K power turbine is the result of an extensive investigation of design shaft power levels at 3000, 4700 and 6400 horsepower in order to select the best aerodynamics for both rated load and off-design conditions. The result is a very desirable flat heat rate curve with power variation, resulting in substantial fuel saving at part power.

A two-stage uncooled power turbine was selected (Figure 13) with a rated output speed of 11,500 RPM and stressed to withstand a maximum speed of at least 150% of rating. In addition, the power turbine is designed to prevent an uncontained failure in the unlikely event of a sudden loss of load with a simultaneous malfunction of the electronic control overspeed protection system.

The problem is common to free power engines. After studying various solutions the designers chose to design a power turbine so that wheels will not burst during overspeed. Normally, a sudden loss of load will result in a controlled overspeed, enabling the control system to command an orderly shutdown. A malfunction of the overspeed trip, however, might allow the power turbine to continue accelerating.

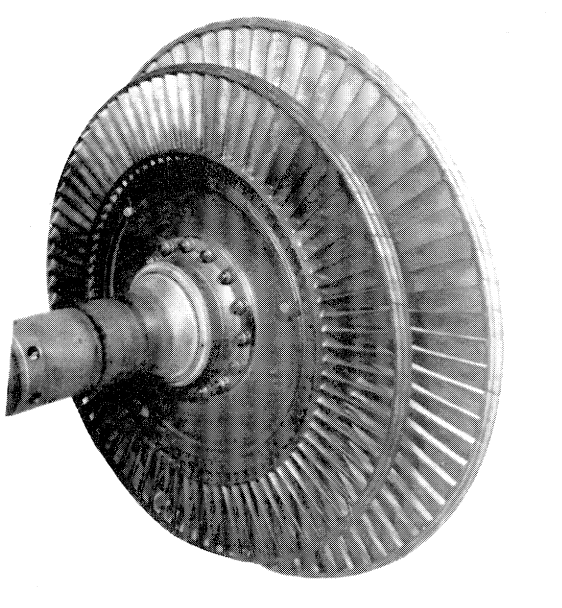

Figure 13. Power Turbine Rotor.

To prevent this possibility from occurring, third-stage blades are designed so that 13 of the 78 blades have reduced stalk area (Figure 14) so that blade damage can be accurately predicted. One or more damaged third-stage blades will cause sufficient secondary damage to prevent further acceleration and thus avoid a wheel failure.

Figure 14. Third Stage Turbine Blades.

MAIN SHAFTING AND MAIN SHAFT BEARINGS

The main shafting is shown schematically in Figure 15, and is basically composed of gas generator rotor, power turbine rotor, drive shaft and torquesensor. The gas generator rotor is a 13-stage compressor drum, stub shafts front and rear, and an

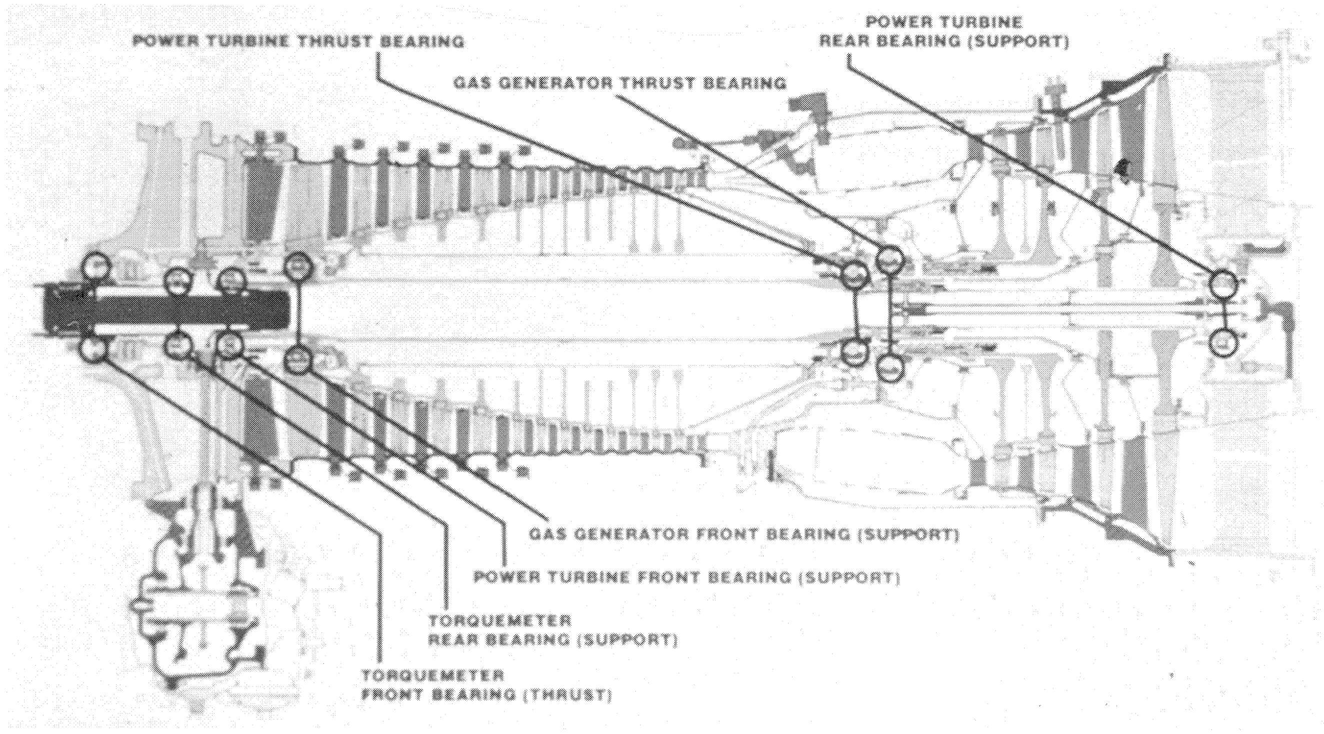

Figure 15. Shaft Support Bearing Locations.

overhung gas generator turbine. The rotor is supported at the front by a roller bearing and at the rear by a ball thrust bearing (Figure 16).

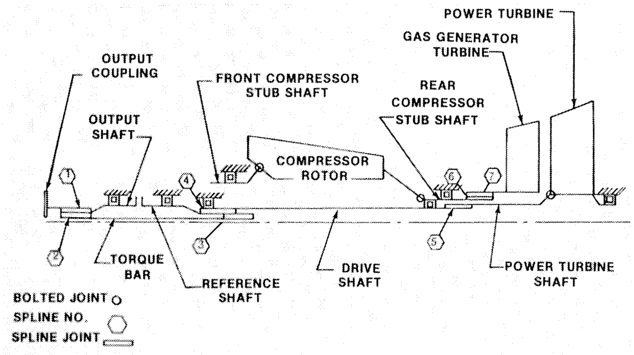

Figure 16. Mainshafting and Rotor Arrangement.

The power turbine rotor is supported at the rear by a roller bearing and at the front by a working spline on the drive shaft. The power turbine is secured on the drive shaft by a power turbine adjusting bolt. The bolt provides axial position adjustment during assembly. The drive shaft is supported at the rear by a ball thrust bearing and at the front by a roller bearing. The front of the drive shaft is connected to a torquesensor by a working spline.

TORQUESENSOR

The torquesensor (Figure 17) consists of a torque shaft splined to the drive shaft at the rear and to the output coupling at the front calibrated to indicate torque as a function of shaft twist. Toothed exciter wheels are attached to each end which passes a magnetic pickup which, in turn, produces the voltage signals. The phase relationship of these signals is proportional to the torque output of the power turbine. The total error in a calibrated system is ±1.73%.

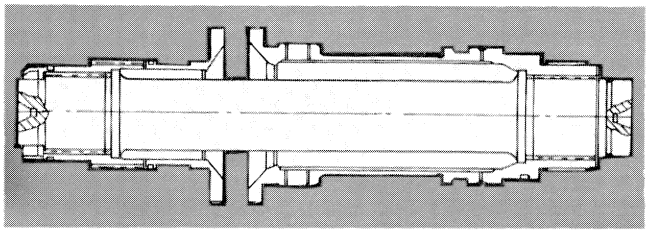

Figure 17. Torquesensor.

ROLLING ELEMENT BEARINGS

The successful use of rolling element bearings on more than 60,000 gas turbine engines developing 317 to 20,000 horsepower made them a logical choice for the 570-K. Such bearings eliminate the requirement for pre/post lube, reduce lube pump flow and power requirement, minimize oil cooler demand, simplify oil venting requirements and permit field replacement of properly balanced and tested compressor and turbine subassembly modules.

Bearing geometry requirements are coordinated with bearing suppliers to benefit from supplier standards, similar operating experience and bench test results. Feasibility studies of the proposed geometry are then made to establish sensitivity to various turbine operating modes. An advanced computer program is used at DDA to accurately model the bearing configuration and its operating environment, resulting in improved life predictions compared to AFBMA procedures.

Working closely with bearing suppliers, DDA then determined the best geometry, fits, tolerances, radial and axial loads, lubrication features including film thickness, contact angle variation and cooling requirements. Exhaustive component tests were then conducted at speeds and loads greatly in excess of operating requirements to confirm the design and ensure long life operation. Grade 5 high quality low tolerance bearings were used throughout the 570-K engine.

SEALS, VENT SYSTEM AND THRUST BALANCE

The 570-K engine is designed to provide cooling air from the compressor throughout the engine to properly balance the labyrinth seals, maintain proper thrust bearing loads and provide positive pressure drop into each of the four bearing sumps to avoid lube oil loss.

All air-to-air seals and air-to-oil seals are of the labyrinth type with abradable material used in stationary positions where seal damage may result in costly replacement.

A portion of the sump vent air is pumped into the scavenge lube oil system and separated at the lube oil reservoir. The remainder is returned to the gas path downstream of the power turbine via a rotating centrifugal air-to-oil separator in the accessory gearbox.

LUBRICATION SYSTEM

The 570-K uses an engine driven combination gear type pressure and 4-element scavenge pump assembly (Figure 18) in a dry-sump system. A nonadjustable by-pass pressure relief valve, set at 60 psig, and a "last change" filter screen are included. The flow is approximately 13 GPM and heat rejection is 1400 Btu/minute. A high quality synthetic lube meeting specification MIL-L-23699 is highly recommended.

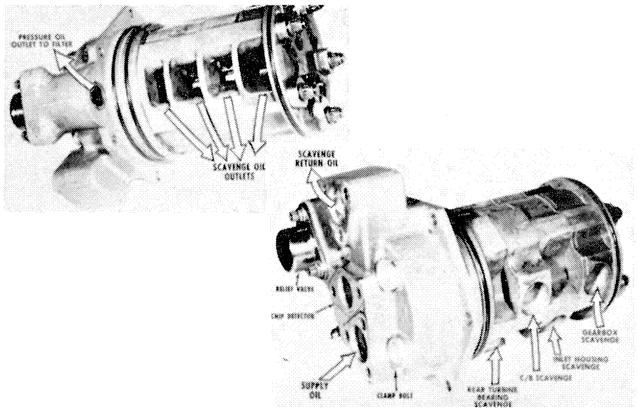

Figure 18. Oil Pump Assembly.

STARTING SYSTEM

A starter drive pad is located on either the front or rear face of the accessory gearbox to accommodate starting with compressed air, natural gas or by a hydraulic motor. Starter torque requirements are identified in engine Specification No. 877B.

FUEL SYSTEMS

Both liquid fuel from an engine driven pump and gas fuel systems are available. Dry filtered gas fuel is supplied to the engine at 275 ± 5 psig where it then enters the engine mounted fuel control valve and is metered according to system requirements.

IGNITION SYSTEM

Ignition of fuel gas takes place on command of the start sequence module of the engine control system. Customer furnished 24V DC power is supplied to a high energy capacitor discharge ignition exciter having dual ignition circuits. Shielded igniter leads and two surface gap igniters complete the system.

ENGINE CONTROL SYSTEM

The 570-K engine utilizes a full authority electronic control system operating on 24V DC electricity. The control includes a logic system consisting of a series of plug-in printed circuit modules mounted in a marinized cast aluminum housing (Figure 19) or which may be combined with additional process control modules and mounted in the customer's control console.

The electronic control unit (ECU) is designed for local and remote unattended start, load and shutdown operation. The unit provides output signals for monitoring critical engine parameters and provides warning and automatic shutdown signals when allowable operating limits are exceeded.

The printed circuitry modules are easily inserted into the ECU and are keyed to prevent modules from improper placement. The following modules make up the complete engine control system:

- Regulated Power Supply
- Measured Gas Temperature
- Gas Generator Speed
- Power Turbine Speed
- Malfunction
- Engine Start/Load Sequence
- Fuel Control
- Compressor Variable Geometry
- Vibration

The malfunction module contains annunciating logic to display any malfunction. There are sixteen malfunction channels, as follows:

- Fail to Crank
- Fail to Fire
- Stagnation
- Low Oil Pressure
- High Oil Temperature
- CVG Position Error
- Fuel System Malfunction
- Measured Gas Temperature — Over Temperature (Figure 20)
- Gas Generator Overspeed/Underspeed
- Power Turbine Overspeed/Underspeed
- Power Turbine Fail to Accelerate
- Vibration Warning/Shutdown

MAINTAINABILITY/SERVICEABILITY

The 570-K industrial gas turbine engine is designed, like other DDA turbines, to be assembled and disassembled into its principle subassembly modules, made to such exacting standards as to be individually replaceable without teardown of the entire engine. This feature permits many in-situ service operations, thus ensuring minimum downtime and maximum availability.

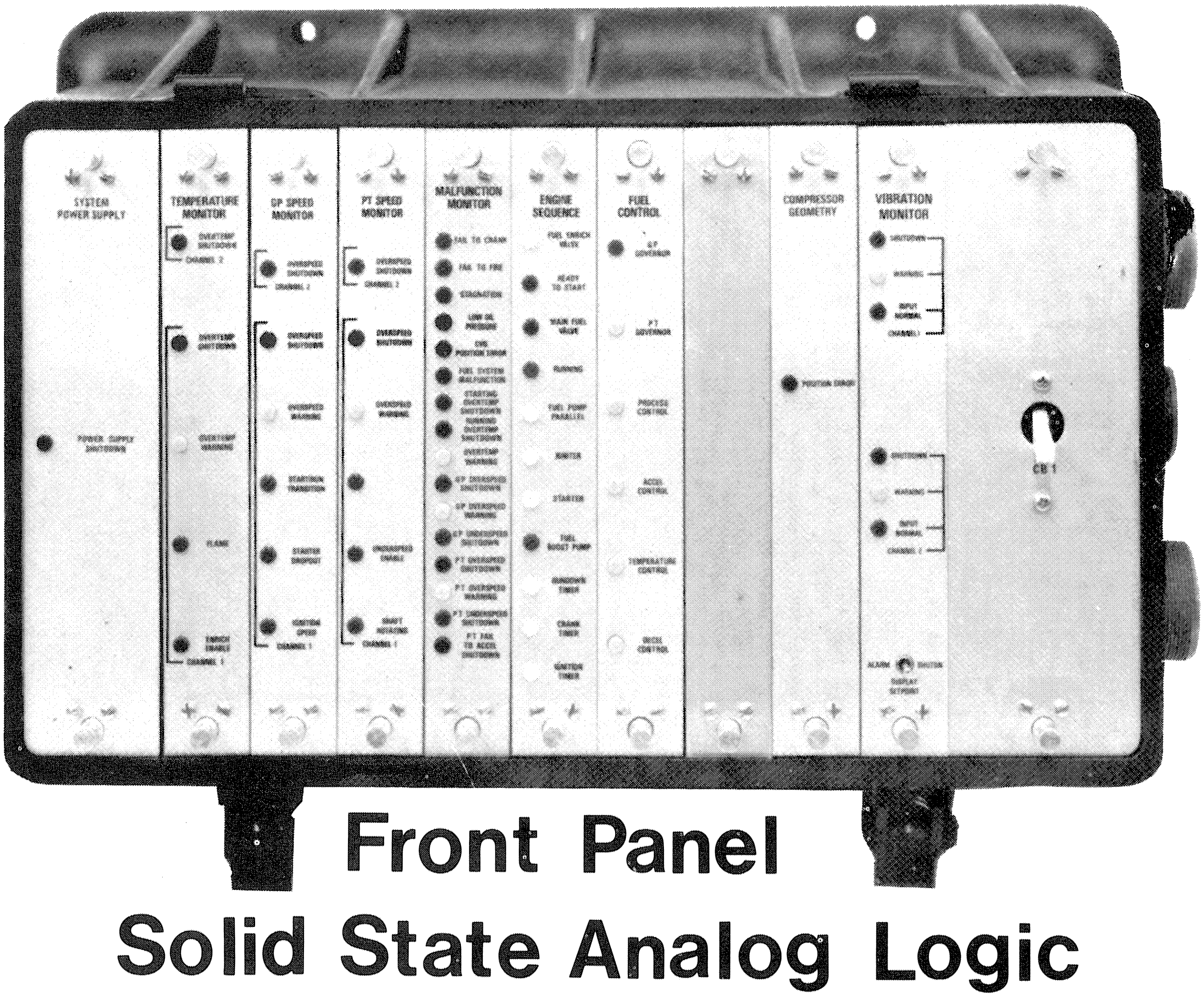

Figure 19. Electronic Control Unit.

In addition to condition monitoring features included with the control system, the engine is well provided with access ports for internal inspection of engine parts without removal of the engine from its installation or the disassembly of the engine. Engine condition and corrective operating criteria can often be ascertained through practiced use of internal inspections.

Recommendations for regular periodic inspection and preventive maintenance based on field experience have been prepared by DDA's field service staff, and service tools have been designed to simplify service activities.

The engine contains no life limited or cycle limited parts. For this reason, "on condition" maintenance is recommended; that is, performing major maintenance in response to a significant change in operating conditions. Such a condition could be a loss of power, high lube oil consumption, high vibration or noise, difficulty in starting or accelerating, hot spots, etc.

Engine condition is largely dependent on the cleanliness of the combustion air, fuel and lube oil so that special attention need be given to ensure that the installation is adequately equipped and maintained with the proper filtration equipment. Extensive experience with both mineral base and synthetic lubes leads to a strong recommendation for synthetics in continuous duty applications. These oils have excellent thermal stability minimizing coke and sludge formation. They have outstanding lubrication characteristics at extremes of high or low ambient temperature with good load carrying qualities and with significantly improved oxidation resistance. This virtually eliminates the need for oil changes.

A maintenance manual is available which describes in detail all service functions for the 570-K engine, including adjustments, calibration, repair and replacement of parts or subassemblies.

SENSING DEVICES

The 570-K industrial gas turbine has a system for measuring gas temperature into the power turbine through the use of nine high temperature thermocouples (see Figure 20) connected in parallel ahead of the third-stage rotating airfoils to indicate average power turbine inlet temperature and to provide an electrical signal to the engine control system for continuous temperature monitoring.

Two piezoelectric accelerometer pickups monitor vertical vibration at the front of the compressor and lateral vibration at

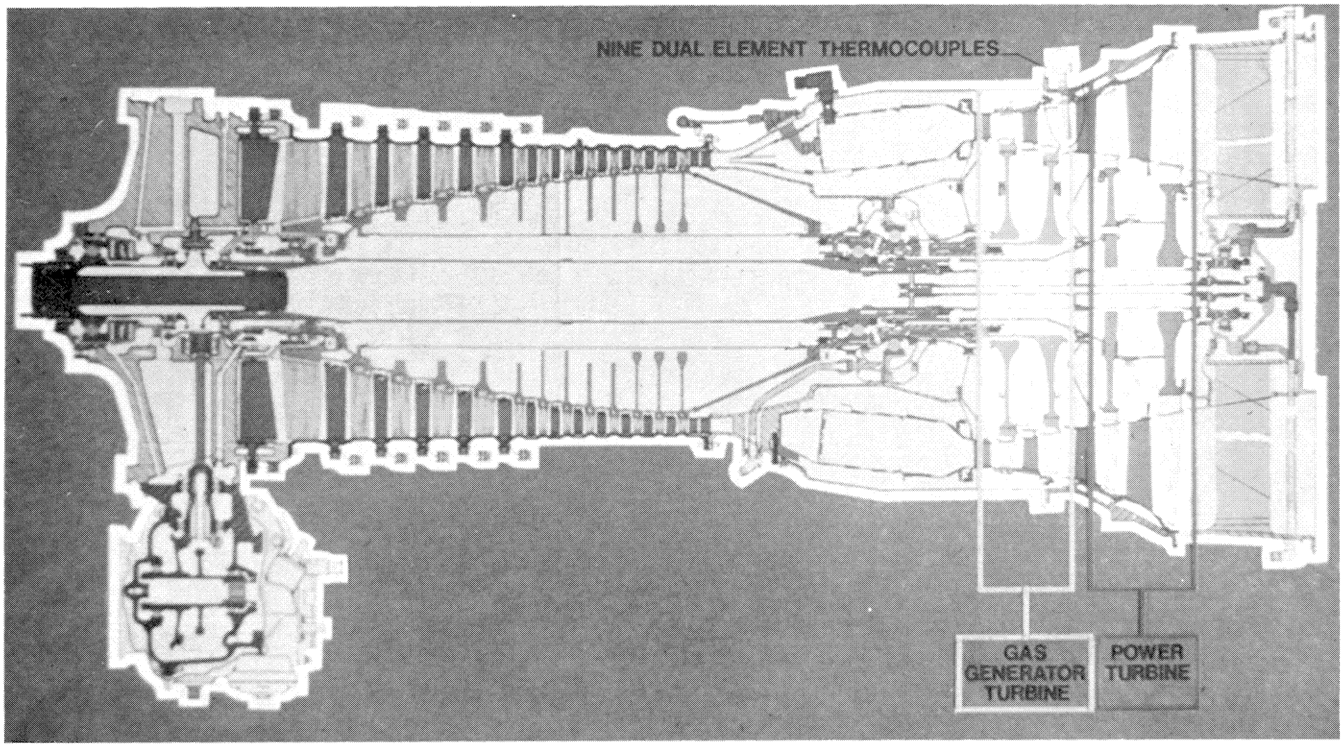

Figure 20. Measured Gas Temperature (Turbine Inlet Temperature).

the rear of the compressor. Electric signals are transmitted to the engine control for continuous monitoring. Speed sensing of both the gas generator and the power turbine is by generating electric signals from the flux density change in permanent magnet pickups when tooth wheels pass the pickup.

PRODUCTION PROGRAM

Production tooling is in place and production 570-K engines began delivery in April 1979. Engines are produced in response to an order forecast reviewed each month with the objective that deliveries can be made within about six months of receipt of order. Option groups are included so as to ensure versatility of engine application to meet not only the requirements of the oil and gas industry, but also satisfy prime mover requirements for electric sets and for marine propulsion drives.

CONCLUSIONS:

Detroit Diesel Allison has designed and proof tested a 6500 horsepower two-shaft engine to be applied in rigorous long life service in an industrial and marine environment. Specifically, the 570-K is intended for gas compression, liquid pumping, and electric power generation both on-shore and off-shore, and it is a superior gas turbine for marine propulsion. Justification for the above is based on:

- Proven components throughout.
- Excellent fuel rate confirmed by experience.
- Metal temperature and stresses well within proven state of the art.
- Materials and coating selected for maximum resistance to corrosive and erosive atmosphere.
- High availability due to ease of inspection, modular repair or replacement.
- Continuous power indication with torquesensor.