CONVERSION OF A SINGLE-SHAFT TURBOPROP ENGINE TO A TWO-SHAFT INDUSTRIAL TURBINE

by

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John Horth graduated from Carnegie Tech in 1943 with a B.S. in Mechanical Engineering. Following service in the Corp of Engineers in WW II, he has spent more than twenty-five (25) years in the design, application and marketing of Turbomachinery. During this time, he was instrumental in the introduction of the T-56 aircraft engine to industrial service, and its later conversion to a two-shaft model—the subject of this paper. He is currently Gas Turbine Marketing Manager for Ingersoll-Rand Company.

The GT-40 two-shaft industrial turbine is a direct off-spring of the T-56 Turbo Prop single shaft engine. This widely used aircraft power plant is illustrated in Fig. 1.

As an aircraft power system, the T-56 consists of the turbine itself, a torque meter, gearbox and impeller. This assembly has a takeoff rating at 60°F and sea level, of 5150 mechanical horsepower plus 800 pounds of jet thrust. As an aircraft engine, it is, of course, designed for wide versatility in terms of ambient pressure and temperature extremes from Arctic to Desert climates.

The T-56 has a 14-stage compressor desigend for 32 lbs/sec of air at sea level and 60°F inlet and with a pressure ratio of 8.5:1. To maintain compressor stability at startup, bleeds are provided at the 5th and 10th stages. These are to be noted since they are significant for the conversion to an industrial turbine, as will be discussed later.

Six (6) cannular combustion chambers are provided and these are designed for operating turbine inlet temperatures up to 1970°F during take-off.

An interesting feature of this engine is the use of direct reading thermocouples at the combustor outlet, as compared to the more common practice of relating reduced temperatures measured further along in the expansion cycle. There are thirty-two (32) thermocouple elements arranged in groups of two (2), the output of which is averaged to give the engine turbine inlet temperature (TIT).

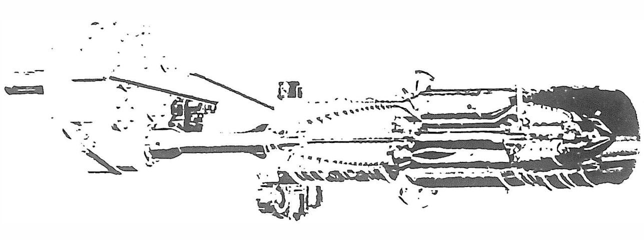

Figure 1. Model T56-A-15 Turboprop Engine. Application C-130.

The four (4) turbine stages of the aircraft engine are a single assembly, the power from which is transmitted forward. That not used for the compressor section is available for mechanical work at the front end through the torque tube system. The assembly of the turbine section is held together by through-bolts but torque is transmitted through curvic coupling interfaces.

This engine was one of the first to employ internally cooled blades. Both the first stage nozzle and the first rotating stage have this feature. The construction of these elements are shown in Figs. 2 and 3.

In the aircraft engine, roller bearings are provided to support the turbine element on each end.

At the inlet end of the compressor section, four (4) pads are provided for shaft driven auxiliaries. These are gear driven from the shaft through the struts in the inlet housing.

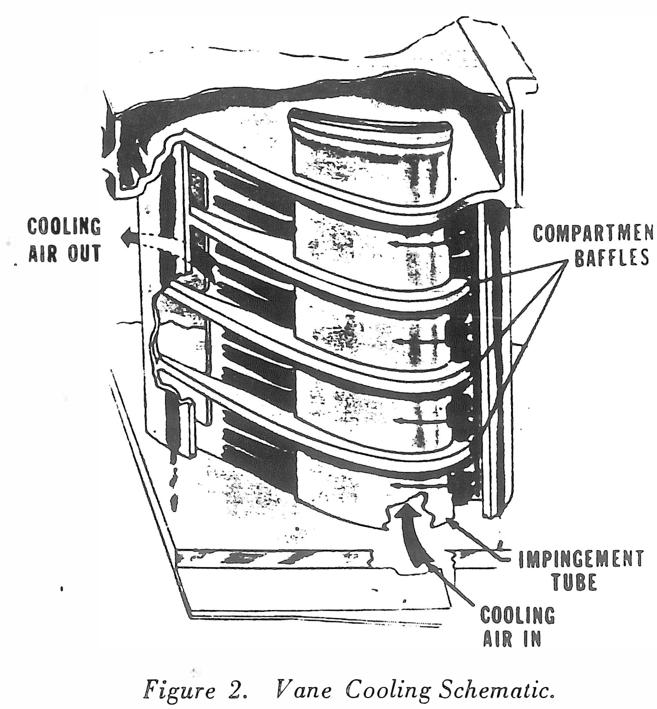

Figure 2. Vane Cooling Schematic.

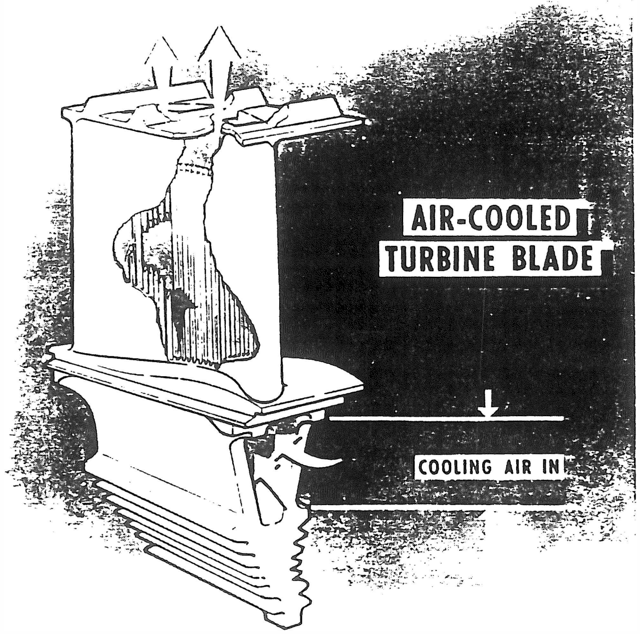

Figure 3. Air-Cooled Turbine Blade.

The T-56 engine completed initial tests and went into production in 1956. Since then, more than 10.000 units have been built by Detroit Diesel Allison, Division of General Motors (DDAD). These power such craft as the Lockeed Electra, Hercules and PB-3 shown in Fig. 4.

By 1963, this engine had demonstrated high reliability as an aircraft propulsion unit and the manufacturer decided to offer it for industrial service. It was, therefore, introduced into gas pipeline and electric generator applications in the original single shaft version. Changes at that time were limited to removal of the aircraft auxiliary components. addition of an industrial governor and development of a gas fuel system to replace the aircraft liquid fuel system. In these applications. the engine continued to drive through the torque meter. providing its power to industrial machinery instead of the propeller.

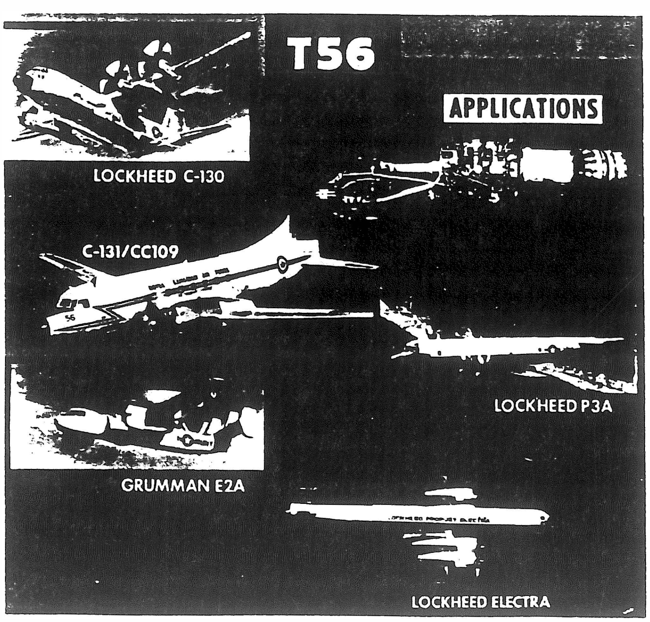

Figure 4. T-56 Applications.

Ingersoll-Rand. as a manufacturer of compressors and pumps. has been employing aircraft derivative turbines to drive their products in industrial service for a number of years. In 1970. they sought a 4000 ISO horsepower industrial prime mover, and made a comprehensive review of the aircraft engines available that might be employed. The T-56 had established the outstanding record of operating in industrial service in excess of 30.000 hours without overhaul. and thereby appeared to be highly qualified for the purpose intended. It suffered from one handicap however—the fact that it was a single shaft engine. This limited its usefulness in two (2) ways:

1. Speed variation was only 12%.

2. As a single shaft engine. it could not be used for applications such as liquid pumps that require a high starting torque capability. Many of the potential uses for a driver in this size range are in liquid pumping, such as oil pipelines. A detailed study of the T-56 revealed that by fortunate coincidence the thermodynamics of the power secion of the turbine split almost perfectly between the 2nd and 3rd turbine stages. In other words, the power of the first two stages was adequate for driving the compressor section and the power of the 3rd and 4th stages was available as mechanical shaft output. DDAD was, therefore, approached for a program of modifying the engine, and agreement was reached between the two companies in June of 1970 to proceed with a joint development. The resultant engine is shown in Fig. 5. As will be noted, it appears remarkably like the original T-56. The same compressor, combustors and turbine rotor elements are used in both. In fact. in the critical aero-dynamic cascade the only changes are: (a.) A two-degree alteration of the 3rd stage vane angle; and (b.) An increase in the stage spacing between the 2nd and 3rd turbine stages of less than ½".

The power turbine takes the 3rd and 4th turbine wheels from the T-56 and mounts them in an overhung configuration from a separate shaft. The wheels are joined by through-bolts as before. and torque is carried through curvic connections. This required the addition of a curvic element on the back of the last turbine wheel and removal of the same element from the 2nd and 3rd stage interface. The wheel assemblies and the stator elements continue to be made by DDAD to minimize hardware change and to take advantage of quantity production.

The power turbine rotor is mounted on two (2) tilting shoe radial bearings in a conventional manner, and a Kingsbury thrust is provided.

Outboard of the thrust bearing, a gear system is built in for driving auxiliaries. These consist of lube oil, compressor seal oil and hydraulic service gear pumps.

The gas generator now referred to as the 501-K16 is bolted by external flanges to the power turbine. Trunnions on the power turbine casing provide the main support for the turbine through a mounting pedestal as illustrated in Fig. 6. Further support is provided above the gas generator center of gravity by a flexible hanger,

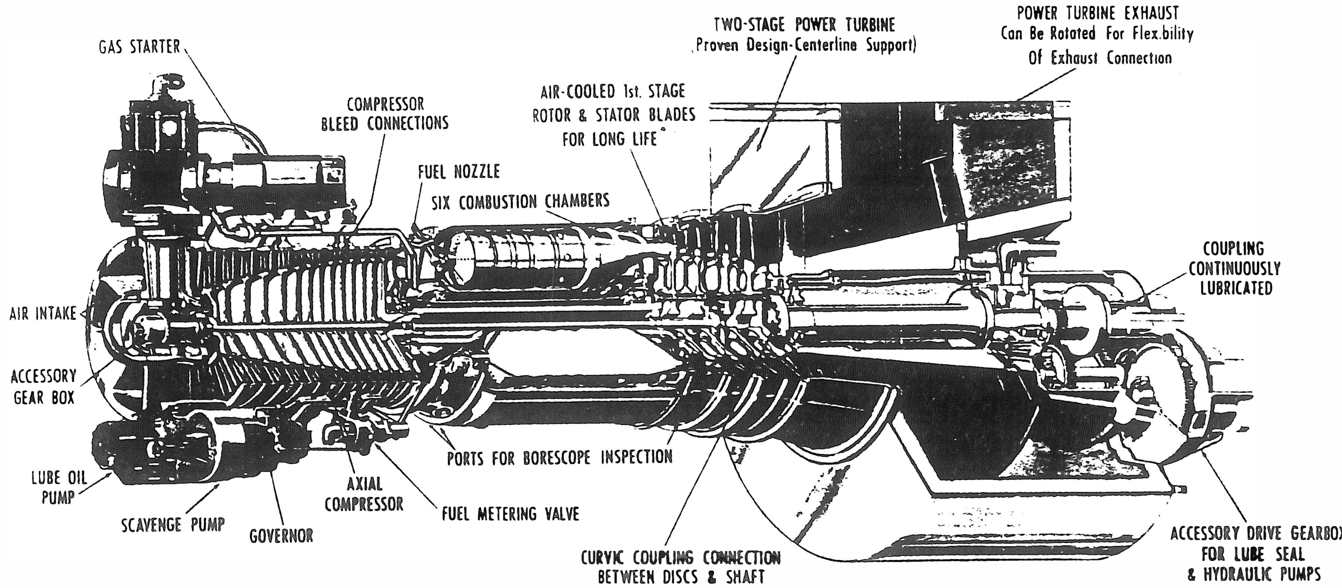

Figure 5. GT-40 Gas Turbine.

its purpose being to carry weight only and allow complete freedom of movement. Within the power turbine, the bearing assembly at the hot end is supported from the casing by a system of struts attached tangentially to the bearing casing. The rear bearing is essentially supported by a flexible plate mounted under the avxiliary gear casing. The turbine diffuser and exhaust collector are supported by struts from the inter-bearing housing in the section surrounding the thrust bearing.

Because the output drive is now taken from the left end of the turbine rather than from the front, the mechanical output through the gas generator nose has been removed. This simply meant leaving off the torque tube and adding a small nose cone to cover the opening.

A starter drive was needed since the aircraft engine starter had been mounted on the propeller gearbox. As mentioned earlier, the engine has four (4) pads at the compressor inlet for shaft driven auxiliaries. For the GT-40, one of these was used to mount a starter gearbox developed for the purpose. This box provides a 1:1 ratio to a vane type starter. On the forward face, the gearbox carries an electrical speed pickup for control purposes. Again, existing hardware was employed to provide the drive from the shaft outward to the starter gearbox.

The bleed connections at the 5th and 10th stages consist of four (4) equally spaced ports for each. In aircraft service, these are operated full open or full closed during the acceleration cycle. This system, however, was not suitable for an industrial prime mover with a wide power and speed range. With only full open or full closed positions, a void band existed in the power plot. The answer lay in modulating the opening of these valves in order to eliminate this gap. Fig. 7 shows the 501-K16A gas generator as built. As will be seen, the bleed ports are manifolded to a single modulating valve for each of the two (2) stages at which bleed takes place. The modulating valves are scheduled as a function of RPM and compressor inlet temperature. The range of full open to full close is approximately 900 RPM as illustrated in Fig. 8. The full gas generator operating speed range is from 10,000 to 14,500 RPM corresponding to a 7000 to 14,500 RPM range for the power turbine.

The gas generator lube system, combustors and thermocouples remain unchanged from the T-56. The gas generator turbine blading is unaltered from the T-56 and the only significant change in this area is in the wheel mounting system.

Previously, the gas generator turbine had bearings on both sides of the wheels. The gas generator turbine stages are now overhung using the same through-bolting and curvic connections as before. The only major modification, therefore, was in the #3 bearing. In the single shaft engine, this is a 60mm roller bearing with a ring spring for vibration suppression between the bearing support and the bearing retainer. The ring has twelve (12) lands on the O.D. and twelve (12) alternately located lands on the I.D. The 0.054 inch thick ring between lands provide the dampening property.

When the engine was modified to the two-shaft version, it was necessary to enlarge the shaft in this section to carry the turbine wheels in the cantilevered arrangement. The bearing diameter was, therefore, increased to 100mm. The design was otherwise retained including the mounting system and the hardware was obtained from the same source as before. Operation has demonstrated this alteration to be fully satisfactory.

Obviously, a basic premise of this program has been to minimize alteration from the aircraft engine to take

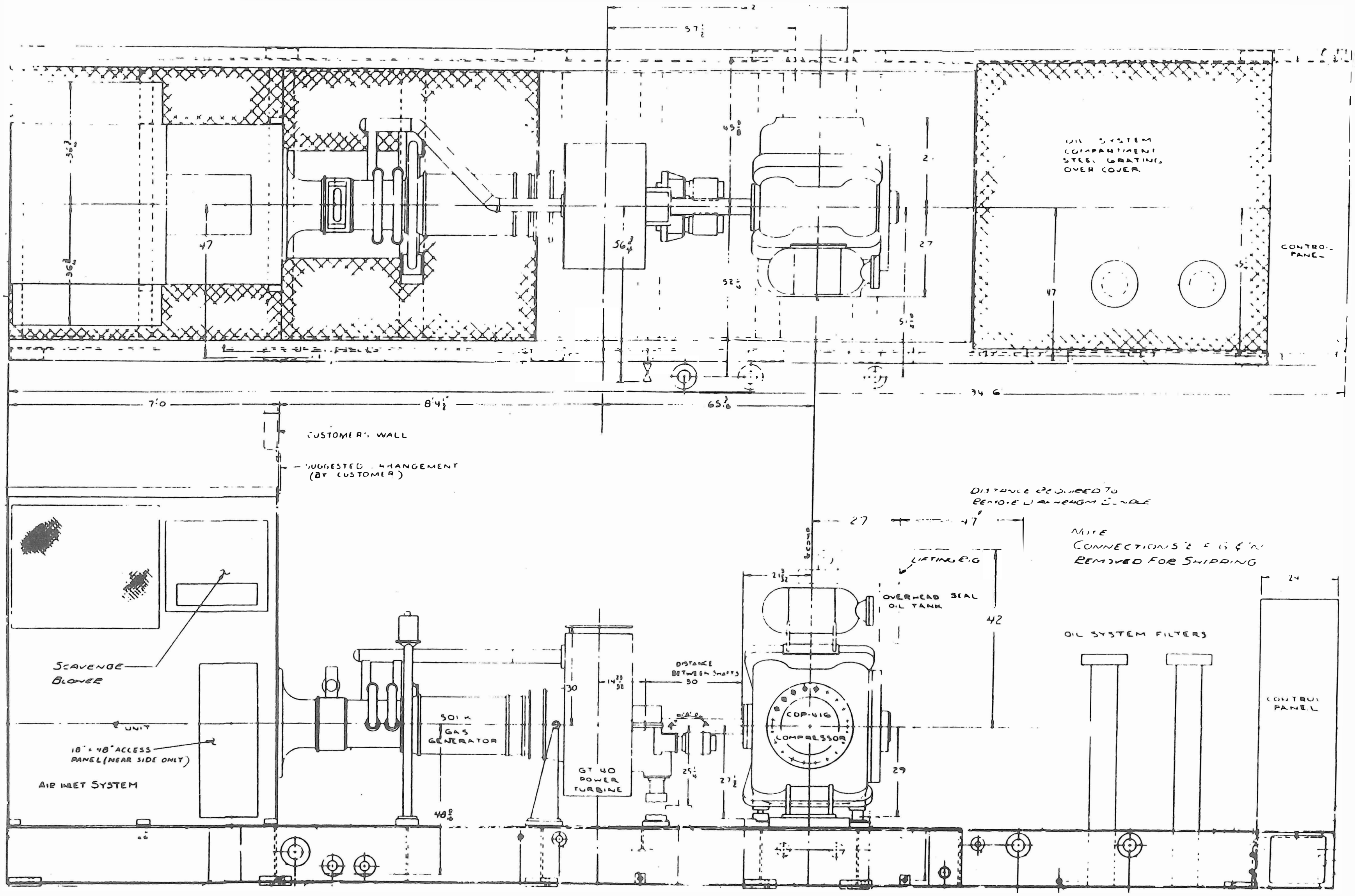

Figure 6. GT-40 Pipeline Compressor Package.

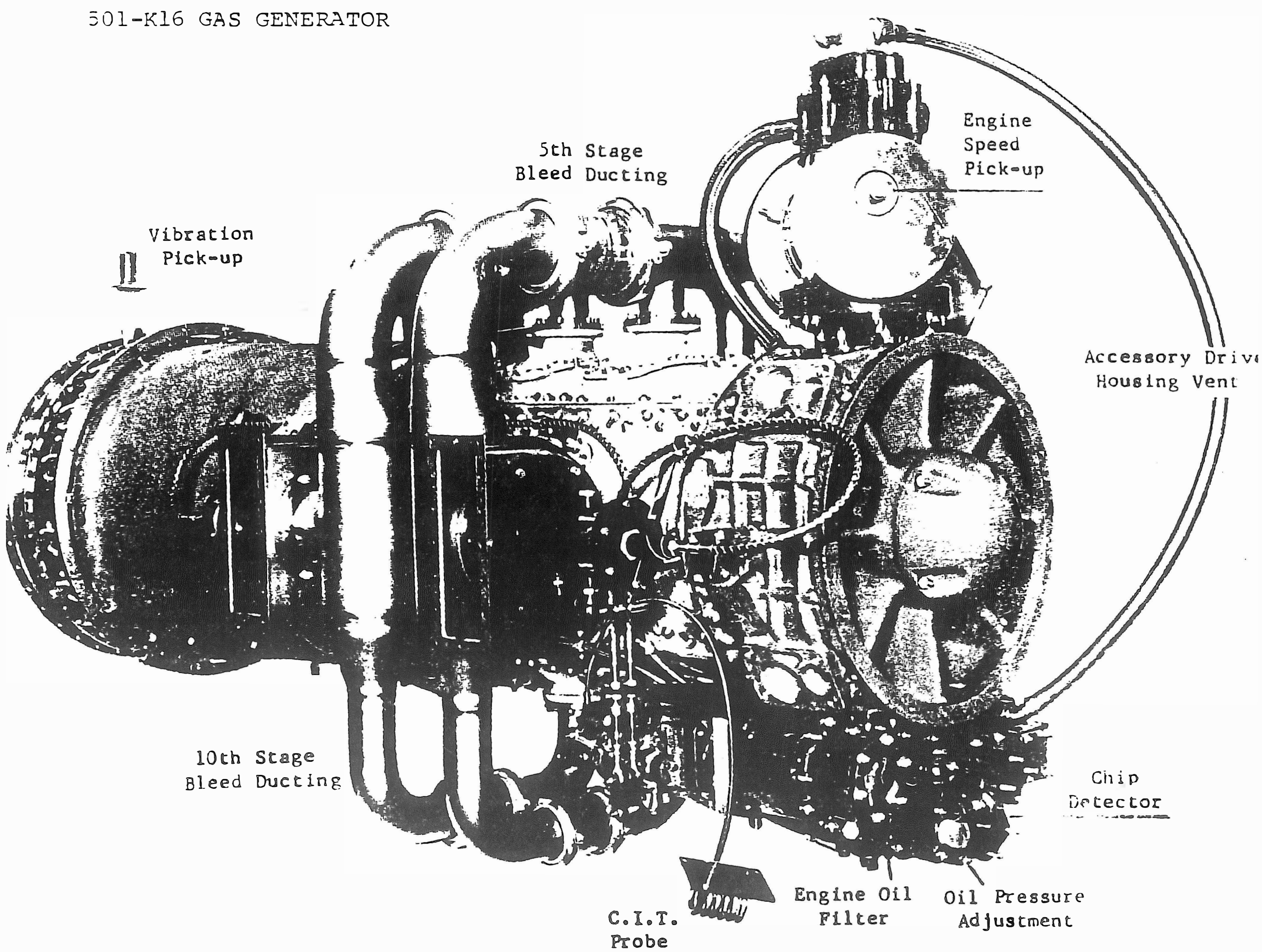

Figure 7. 501-K16 Gas Generator.

advantage of quantity production but even more compelling reason was to receive the benefit of the total experience of the T-56. On 10,000 units monitored over a period of 17 years, this experience is considerable and places the engine far down on its learning curve. Therefore, all elements of the basic aircraft turbine useful in industrial applications have been kept the same wherever practical, including metallurgy. One important area is the knowledge gained from Naval programs on handling salt air corrosion (sulphidation). This is particularly valuable for the many offshore platform applications to which the industrial engine will be applied. This engine was the first to pass a 3000 hour Naval Endurance Test ingesting salt-laden air. From that extensive testing program, current practice of INCO-738 blading and X-40 vanes with Alpak coating was developed for units destined for use in marine environments.

Conversely, it is interesting that the aircraft engines have benefited from the industrial program because of the accelerated calendar time from which they accumulate long hours of operation.

The first 501 gas generator was delivered in the summer of 1971 following prototype testing by the manufacturer for performance and mechanical integrity. These tests were conducted under load against calibrated nozzles. This practice continues to be followed for production units. The completely assembled GT-40 then underwent a test program at I-R loaded by a shop water brake. Approximately 300 hours were accumulated before shipment of the first unit in late 1971. These tests closely confirmed predictions on the unit output, which would be expected since the aero-dynamic components were of known characteristics. The characteristic of the engine is shown in Fig. 9 for ISO conditions at sea level and 60°F. As will be noted, this turbine has an unusually broad range of speed at maximum power. The rating is based upon a T.I.T. of 1800°F. This is a deration of 170°F from aircraft take-off levels and with the benefits of internally cooled blades results in an average metal temperature in the first stage of approximately 1510-1520°F, which is within the creep limits and stress rupture parameters for the metals used for a targeted life in excess of 100,000 hours.

During the shop prototype test, only minor modifications were found necessary. These included some alteration of the flexible support and piping on the

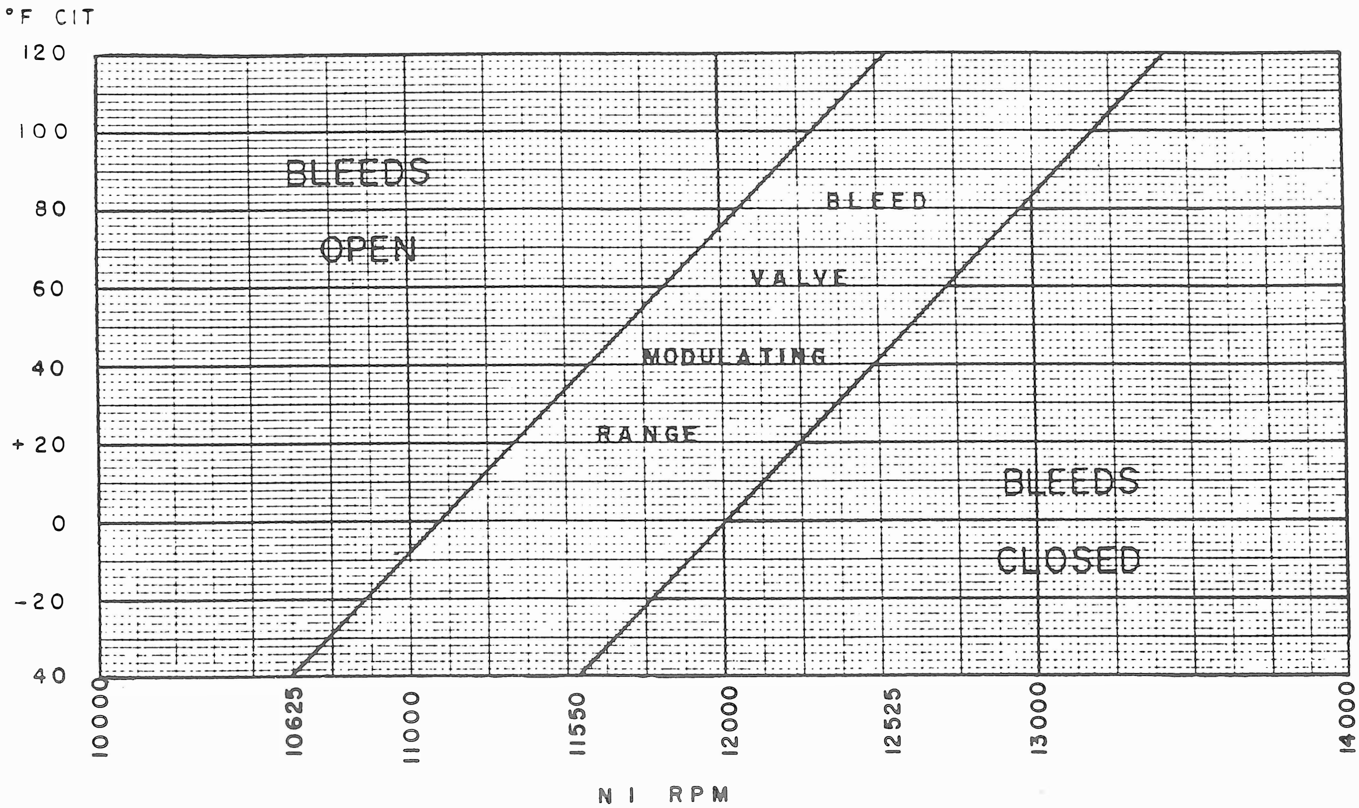

Figure 8. 501-K16A Engine—Acceleration Bleed System Actuating Range.

coupling end of the power turbine, an alteration of the method of mounting the auxiliary gear pinion on the power turbine shaft, and a change in the support of the bleed duct leading from the modulating valves to the turbine exhaust.

The first unit was placed in industrial service in February of 1972 by Cities Service as a gas pipeline compressor driver. To date, this engine has accumulated over 12,000 hours. Subsequently, nineteen (19) units were made operable on Oasis Pipeline in the fall of 1972.

Experience with the turbine to date has been highly gratifying. No problems have been uncovered in the design of the gas generator portion. In the power turbine section, the basic system has likewise proven sound. The one area that has required correction has been in the auxiliary gearbox. Several failures were experienced in this section. These were fatigue failures of the gear teeth particularly between the idler and the pump pinion for the seal oil pump. Simultaneously, there were several ruptures of flexible oil lines connecting these shaft driven pumps to the system.

These difficulties proved to be caused by pulsations originating in the gear type oil pumps that were transmitted to the gears by splined couplings of limited flexibility used in the original design. The situation has been corrected by softening the system through replacement of the coupling with more flexible types and introduction of more flexible hosing on the oil lines. As insurance, the gear faces were widened by 5/16 ins. to reduce tooth loading.

A turbine by itself remains an academic curiosity unless supported by a broad design effort to apply it in a useful manner. This involves a carefully engineered program of comprehensive packaging with driven equipment, and a discussion of this turbine development presents only a partial picture without a few words about this supporting effort. Fig. 6 shows the general configuration adopted for the GT-40.

The change from the front drive of the single shaft turbine to an aft drive and the location of the auxiliary gear at the coupling end of the turbine has permitted location of the inlet filter-silencer on the bedplate and a straight flow path into the turbine bellmouth. The standard filter configuration has been designed to accept either inertial, replaceable media, or mist eliminator filtering elements. Within this configuration, various degrees of silencing are available depending upon the requirements of the jobsite. The inlet system can also be equipped with evaporative cooling for applications with a dependable low dry bulb temperature. For such applications, a power increase of 15% or more is possible.

The units can be furnished with sound enclosures around the turbine or without. The same applies for enclosures around the driven apparatus.

The lubrication system is common for the gas generator, the power turbine and the driven equipment. A reservoir is built into the baseplate and oil filters and other equipment are included within the section adjacent to the control panel. Because this is an aircraft derivative turbine, synthetic lubricants meeting EMS-53 are employed.

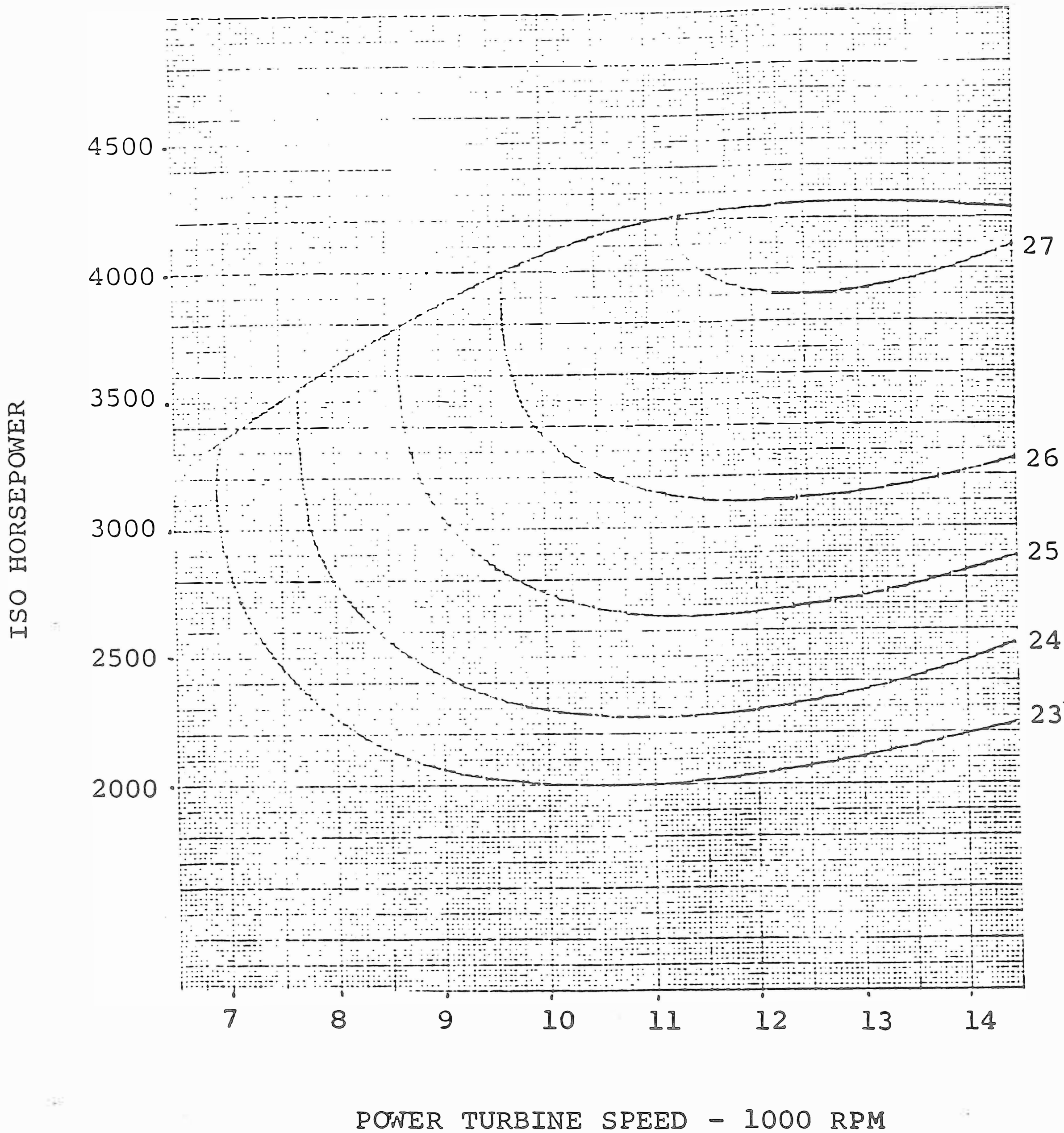

Figure 9. GT-40 Gas Turbine. ISO Performance (60°F at Sea Level). TIT = 1800°F.

Exhaust silencing can be provided to meet various noise requirements as specified. The package configuration includes a support structure for the exhaust when needed.

Controls are furnished for complete automatic operation. These can be mounted on the baseplate in explosion-proof housings or they can be mounted off the baseplate, if preferred. In any event, the baseplate is fully wired, and for the remotely located panels all leads are brought to an explosion proof terminal box on one end.

Because of the variety of fuel requirements encountered, gas, liquid and automatic dual fuel systems have been developed.

A high degree of factory packaging also requires a capability for full factory testing since the principle function is one of minimizing field labor and field correction of flaws. Each unit, therefore, is shop tested along with its own driven device—pump or compressor.

In a program of this type, it is sometimes possible to use existing pumps and compressors from the manufacturer's prior designs. To obtain maximum benefit, however, new driven machines are also needed. Fig. 10 illustrates a pipeline compressor developed for direct connection to this high speed turbine. This compressor is intended for gas volumes and ratios commonly encountered in Gas Transmission and can accept from one (1)

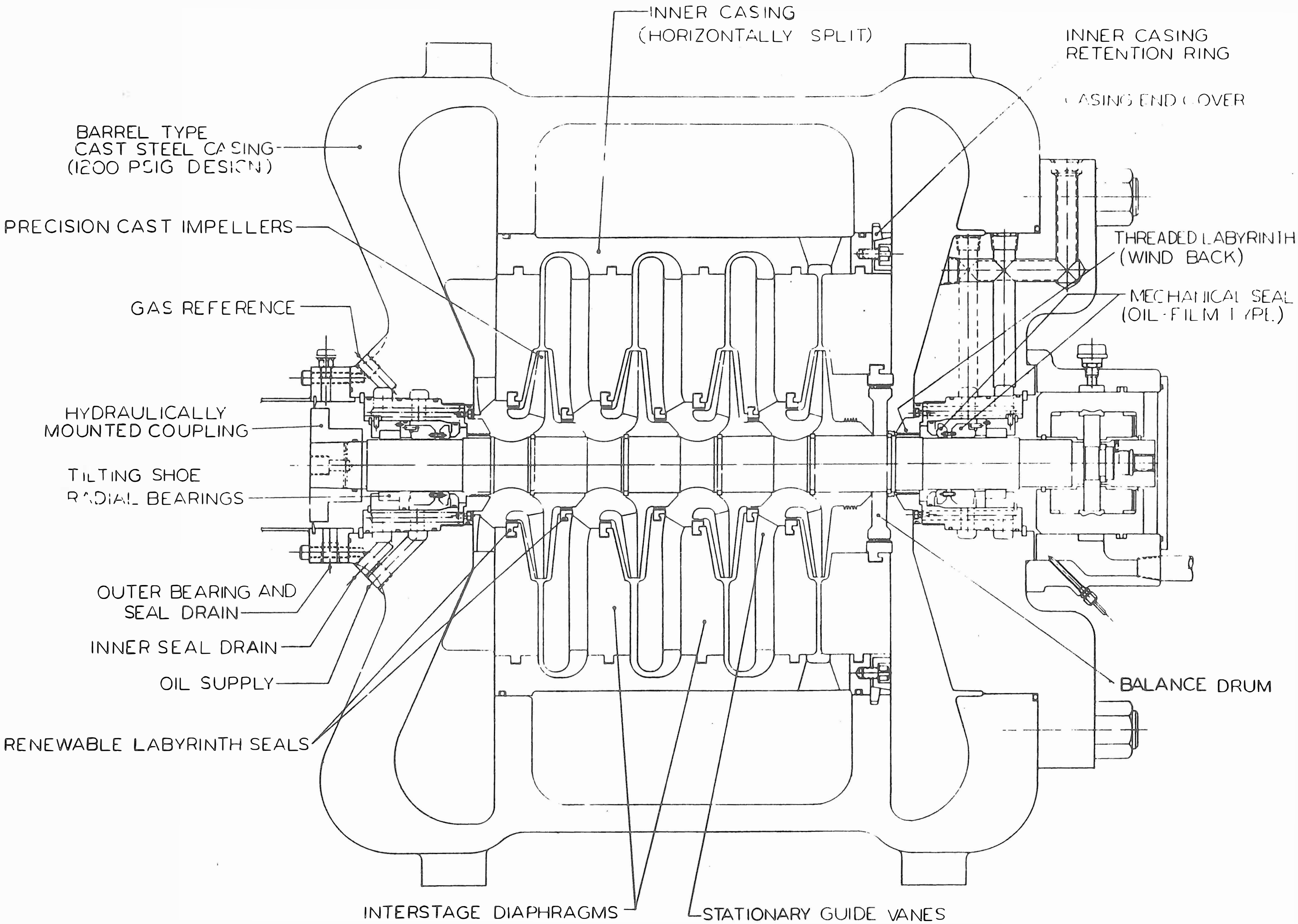

Figure 10. CDP-416 Compressor Assembly.

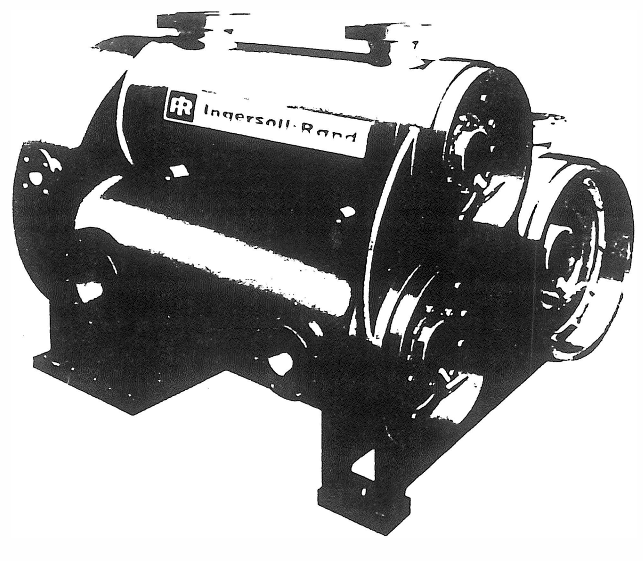

Figure 11. Centregal Compressor.

to four (4) stages of compression in series or two stages in parallel at higher volumes.

Of particular interest is the high compression ratio centrifugal with the trade name "CENTREGAL" designed to make the turbine useful in ranges, heretofore, largely limited to reciprocating machinery. This unusual machine is illustrated in Figs. 11 and 12. It consists of three (3) multi-stage centrifugal compressor casings mounted in a single bundle and directly connected to the turbine by a built-in speed increasing gear. This machine

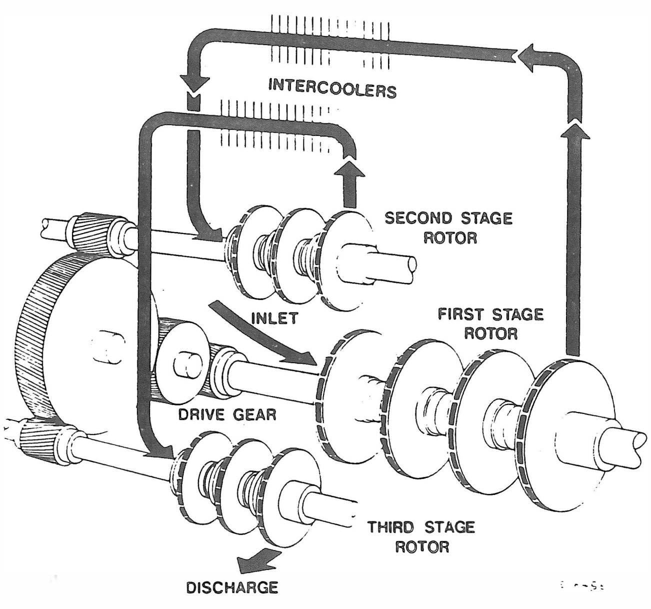

Figure 12. Centregal Compressor Flow Schematic.

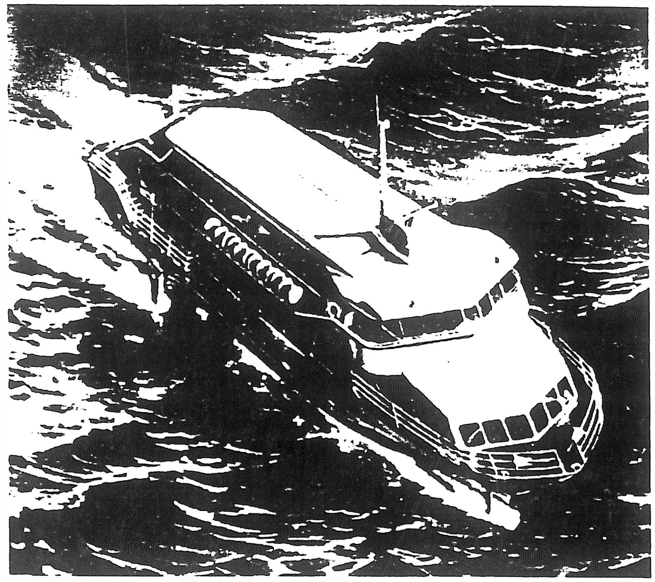

Figure 13. New 250-passenger Hydrofoil Designed by Boeing Company.

will handle flows of 3000 ICFM or less at compression ratios up to 25-30:1. With the very small flows encountered, particularly toward the top of the compression cycle, higher than normal speeds are required for the best aerodynamics. The number 1 rotor in the case operates at 20,000 RPM and the 2nd and 3rd elements run at 30,000 RPM. The particular virtues of this compressor are high efficiency combined with the elimination of couplings between multiple casings strung out in a line. Intercooling, of course, is required between casings on high ratio applications and this is done external to the compressor. A total of thirteen (13) impellers can be installed or a lesser number if less than maximum ratio is needed.

A novel feature of this compressor is the introduction of dry face seals in place of conventional oil seals generally used in high pressure gas compressors. The dry seal eliminates the complexities of the seal oil system.

Another interesting use for this turbine has been to drive small ships. Fig. 13 illustrates the new, 250 passenger hydrofoil designed by the Boeing Company. Propulsion of the ship will be provided by two (2) of these turbines driving water jet pumps.

Two shaft turbines of this size have many uses throughout the world including gas pipelines, oil pipelines, gas and oil production platforms, LNG plants and other processes. In less than two (2) years 100 of these units have been sold for such applications and increasing useage is anticipated, particularly in rapidly expanding remote areas of the world where pre-engineered, packaged compressors and pumps are needed to combat the energy crunch.