

INDUSTRIAL APPLICATIONS OF AIRCRAFT-DERIVATIVE GAS TURBINES

by

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INTRODUCTION

The aircraft-derivative gas turbine as a stationary ground-based prime mover has achieved a spectacular record in its short history of 13 years. During October 1960, in a remote Kentucky gas compressor station located on Possum Trot Ridge, Columbia Gulf Transmission Company commenced operation of the prototype unit for base load industrial duty. The 10,500 BHP gas turbine package, made up of a Pratt and Whitney Aircraft modified J-57 plus a Cooper-Bessemer RT48 free power turbine, was utilized to drive a centrifugal pipeline booster to compress 10 tons of natural gas per minute from 750 PSIG to 950 PSIG through a 24-inch diameter pipeline.

At that time, the prototype program was primarily intended to demonstrate that an aircraft-derivative gas turbine could operate a period of 8000 hours without requiring major maintenance. Aircraft J-57 engines were operating 1400 hours between overhauls and only a field prototype experience could prove the integrity of seals, bearings, and auxiliary components. It was a high risk adventure and perhaps the first major attempt to translate aircraft technology to industrial uses. It is interesting to reflect that no comparable attempt was made to translate aircraft reciprocating technology to industrial applications in the years prior to the advent of the aircraft jet engine.

DEFINITION

This paper will be directed only to industrial base-load applications of aircraft-derivative gas turbines, and their requirements. No attempt will be made to describe the peaking power generation or the marine markets, although very sizable segments of the overall gas turbine industry, carry unique requirements and experiences.

Base load applications are those calling for a very high utilization factor. There are 8760 available hours

in the average year and typical base load utilization involves operation of equipment between 7500 and 8760 hours per year over the project life. 8000 hours per year would be typical of gas or oil pipeline operation whereas 8700 hours per year would be typical of chemical or refinery operations. In all cases, the product being handled has a high market value and the user selects equipment that will be highly reliable and available for use in his system. To minimize scheduled plant downtime, the "base load" used will also select equipment that requires a minimum of inspection and major maintenance. Typically, the user will specify equipment requiring inspections on an annual basis with major maintenance after three years of operation.

Manufacturers, in turn, must carefully rate their equipment to satisfy the user requirements. Turbine inlet temperatures, operating speeds, and materials must be optimized to achieve the longlife criteria. Generally, the rating for industrial service approximates an aircraft engine in the "cruise" condition. The "take-off" ratings for an aircraft engine are seldom used in the base load application due to the high maintenance trade-off. Commonly, this reserve power is utilized for the emergency or "peaking" power generation application, where high specific output is desired for infrequent periods of operation.

The *jet gas turbine* consists of two major components—an aircraft-derivative gas generator and a free power turbine. The *gas generator* serves as a producer of gas energy or gas horsepower. It is derived from an aviation gas turbine engine in that fuel system and control modifications are made to burn applicable industrial fuels, and design innovations are incorporated to insure the required long-life characteristics in the ground-based environment. Typically, it serves to raise combustion gas products to conditions of 30 PSIA and 593° C. (1100° F.) at the exhaust flange.

The *free power turbine* serves to convert the gas energy to mechanical rotative energy or brake horsepower. Closely coupled to the gas generator by a transition duct, the power turbine expands the gas generator combustion products through one or two turbine stages and the residual gas energy is exhausted to atmosphere. The rotative power produced in the power turbine is then available for mechanical couplings to the driven equipment. The power turbine is not aircraft derived and is generally designed and manufactured by the package supplier.

The package supplier becomes the prime contractor in furnishing the complete jet gas turbine, which includes as well the baseplates, oil systems, fuel and governing systems, and control panels for operation and protection

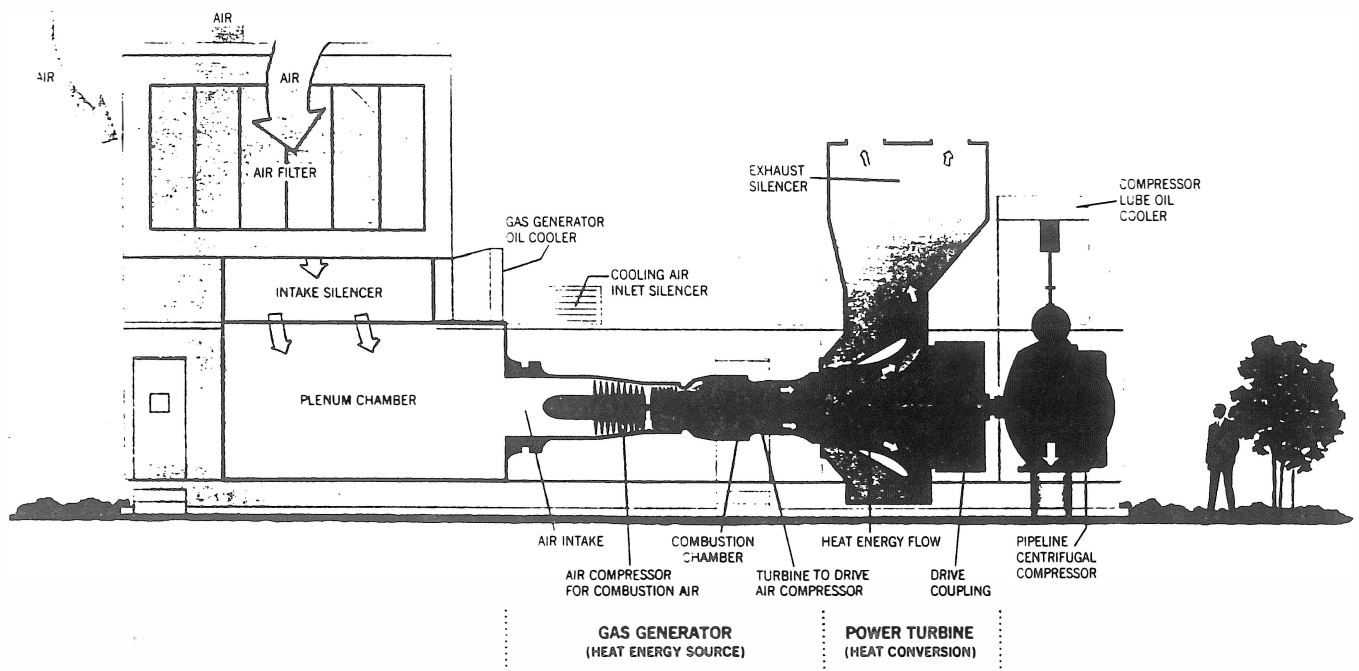


Figure 1. Jet gas turbine—schematic of equipment arrangement.

(see equipment schematic, Figure 1). The equipment and auxiliaries are then factory assembled and mechanically tested as a package prior to delivery to the installation site.

COMPETITION

The entry of the jet gas turbine for base-load use was not simply a matter of demonstrating a successful prototype unit. Conventional or "heavy-duty" stationary gas turbines were designed shortly after World War II and had been introduced into base-load service in the early 1950's. A great deal of operating experience in a variety of applications had been accomplished prior to initiation of the jet gas turbine concept. The early heavy-duty gas turbine design philosophy largely was an extension of stationary steam turbine designs. Since weight and space restrictions were not important parameters, design characteristics included heavy wall casings split on horizontal centerlines, sleeve (hydrodynamic) bearings, large diameter combustors, thick airfoil sections for blades and stators, and large frontal areas. Overall simple-cycle efficiencies were low and regenerative-cycle designs were introduced to obtain higher cycle efficiencies.

Needless to say, the jet gas turbine's introduction in the early 1960's created a proper share of skepticism and raised eyebrows as would be expected in an innovative concept. Consider the design philosophy of the jet engine designer who faces criteria of weight, altitude, temperature, and size substantially different from the stationary prime mover designer. In this case, the resulting gas turbine product features lightweight casings of annual design, anti-friction (ball and roller type)

bearings, small auxiliary modules, and minimum frontal areas with corresponding reduced rotor and combustor diameters. Power-to-weight ratios and simple-cycle efficiencies were high due to the state-of-the-art component efficiencies and the use of high temperature superalloys. When introducing this design for industrial service, the anti-friction bearing system was the largest unknown as bearings of this type had never been utilized in high horsepower base-load machinery and design techniques were known only to the aircraft industry.

Despite the initial differences in design objectives, the skills and technologies have moved towards each other over the years. Materials and turbine cooling techniques evolving from aircraft developments have flowed to stationary industrial gas turbines. Aircraft-derivative gas generator components and auxiliaries have been improved for increased life and reliability using techniques familiar to the heavy-duty machines. As will be discussed later, the trend has been set for continued blending of the best of the two technologies.

One other interesting observation is the flow of the base-load experiences on jet gas turbines back to the aircraft designs of the same engine. In the early years, it was assumed the vast quantity of aircraft engines in service would continually feed durability improvements to the industrial units. However, the base-load units accumulated time so rapidly that operating hours per given engine quickly surpassed that of their aircraft counterparts. As a result, as problems arose and rectification schemes were devised for the industrial units, these schemes became available to the benefit of the aircraft engines.

DEVELOPMENT PROGRAM

The development problems in adapting the aircraft-derivative gas generator to the ground level environment have been well documented within the technical societies. In brief, the ground level air density environment created two situations in the early days that required design modifications. First, the greater air density (compared to air density at 30,000 feet) created more aerodynamic buffeting than expected in the combustion chambers to the point where heavy wear occurred and caused eventual breakup of the chamber locating surfaces. Design changes were necessary to improve the clamping and fitting of rubbing surfaces, plus the addition of chrome carbide flame plating to improve wear resistance. This treatment was very effective and combustion chambers are rarely a life-limiting component today. Second, the air density had to be allowed for, in controlling the axial loads on the gas generator rotor thrust bearing. To prevent an overload on the thrust bearing, which is a ball-type bearing, an air seal is attached to a compressor disk and sized to limit the air pressure acting on the air compressor and ensures that the axial load remains within design limits throughout the operating range. As an example of the effectiveness of this design scheme, the Rolls-Royce Avon gas generator has not experienced a mainline bearing failure in over 2 million hours of operation in base-load applications.

Another problem area that became evident after several years of experience was the reliability of the aviation auxiliary modules, which contain the engine driven oil and hydraulic pumps and control systems. After accumulating several years of experience, it appeared the basic gas generator liability was being limited by the reliability of the auxiliaries—a not too uncommon problem in the development of all prime mover machinery. Considerable work has been undertaken to improve the integrity of auxiliary drives, pumps, governors, variable guide vanes and bleed valves. In one case, Cooper-Bessemer and Rolls-Royce jointly developed a program to delete the entire aviation auxiliary module and replace it with an off-engine system made up of selected industrial-type auxiliaries. The program succeeded in increasing over-all reliability of the jet gas turbine package as well as reducing auxiliary system maintenance and operating costs.

MAINTENANCE CONCEPT

The maintenance concept inherent in the jet turbine is worth noting in some detail as it is a factor that sets it apart from competitive machines. Similar to aviation practice today, industrial users have found the "black box" method of maintenance to be attractive and of economic value in their system operation. Basically, this involves the "changeout" of the gas generator for scheduled or unscheduled maintenance, and its replacement with a spare engine—an operation involving three to six hours elapsed time. Spare gas generators are either owned, leased or exchanged by the user, dependent on unit population and plant requirements.

The gas generator requiring maintenance is then transported to a maintenance base qualified to inspect, repair, recondition, and test the model involved. With the increasing number of jet gas turbines in service (in the order of 1000 units in North America), aviation maintenance facilities are tooling up for the increased

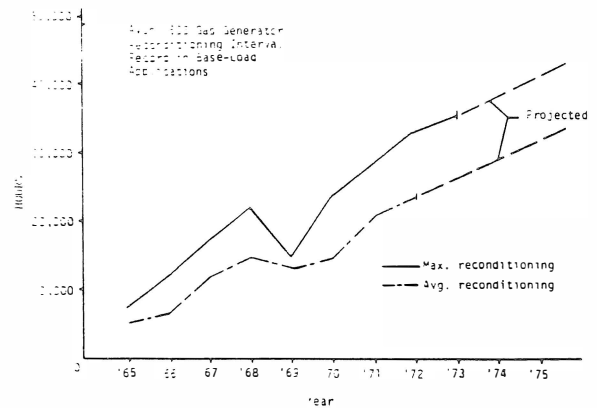


Figure 2. Avon reconditioning record.

industrial requirements. Presently 14 maintenance facilities are in operation for industrial work in North America, broken down as follows: Airlines, 2; Manufacturers, 7; Independently-owned, 5.

The user benefits economically in that he does not require investment in 1) specialization and training of maintenance personnel; 2) parts inventory required for the shop repair or reconditioning; and 3) supervision and administration required to conduct an "in-house" maintenance program. In addition, periods of reconditioning are utilized to incorporate durability modifications designed to improve engine performance and reliability. This practice is direct from the aviation industry and is enthusiastically accepted by the industrial user, although the procedure was considered unusual initially. In fact, gas generators are continuing to self-improve durability-wise as after each reconditioning it is projected to achieve a longer life expectancy than its previous operating cycle (see Fig. 2).

From a maintenance cost viewpoint, the increase in life expectancy (gas generator reliability) has more than offset the increases in material and labor costs. Using the Avon as an example (Fig. 3), average costs of reconditioning have increased from \$30,000 to \$45,000 over a seven-year period, but actual cost/operating hour has decreased due to the longer life expectancy.

Because of the changeout concept, the overall downtime of a given jet gas turbine powered unit or plant is significantly less than for the conventional gas turbine, or any other stationary prime mover. All other types of equipment require on-site inspections, repairs, and overhauls and the downtime involved can range from two days for a routine inspection to 30 days for an overhaul. As most base-load applications involve a high cost of product, wherein outage costs can vary from \$10,000 to \$100,000 per day, the savings gained by brief interruptions, as opposed to more lengthy although less frequent intervals, become a significant consideration in overall plant economics.

Field experience has also determined that a great number of on-site repairs and adjustments can be made with the gas generator remaining in the package. These operations are akin to field maintenance techniques developed by the airlines and the military. Field inspection

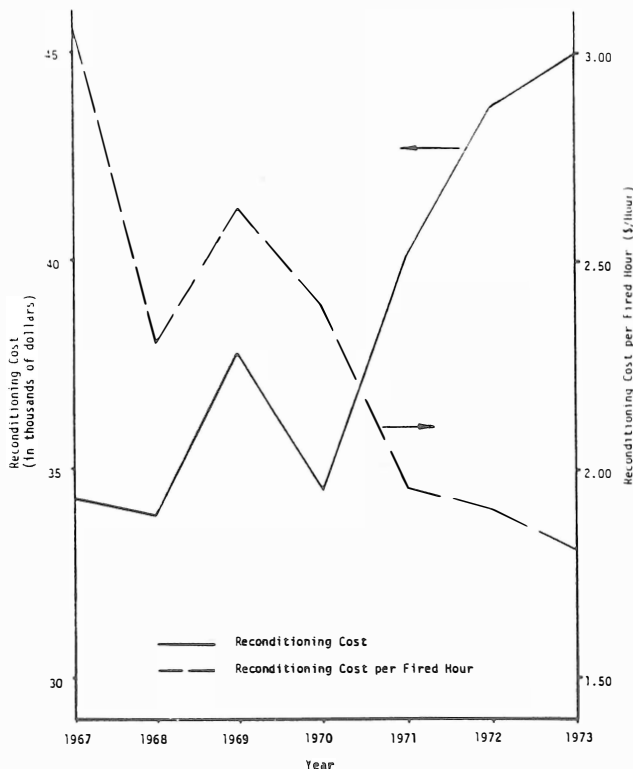


Figure 3. Gas generator reconditioning costs, 1967-1973.

techniques using boroscopes, vibration and temperature analysis, and infrared pyrometry serve to aid in diagnosing engine performance. Obviously, any repairs that can be made on the gas generator on-site in a timely manner will eliminate a time consuming roundtrip to a maintenance facility. Examples of such operations include replacement of inlet guide vanes and first stage compressor blades damaged by foreign objects, inspection and/or replacement of fuel nozzles and combustion chambers, replacement of auxiliary system modules—all operations requiring less than eight hours.

In one unusual situation, an engine was repaired in Western Canada by undertaking a bulk disassembly of the unit in a space adjacent to the skid. The supervision and special tools were supplied by the gas generator manufacturer in this case. The gas generator was placed on its nose in a fixture and each major assembly (exhaust unit, turbine shaft and rotor, nozzle vanes, and combustors) was removed to gain access to a faulty bearing supporting an auxiliary driveshaft. Upon replacement of the faulty part, all other parts were reinstalled; however, any components could have been replaced had it been necessary. The repair work in this case required 24 hours, with the total downtime of the plant, including removal and reinstallation, amounting to just 37 hours.

Future maintenance techniques, for new generation of gas generators, will involve modular replacement of assemblies rather than replacement of complete gas generators. These new engines are designed for easy modular disassembly in the horizontal position and therefore the reconditioning exercise can be limited specifically to a compressor, combustor, or turbine module.

In summary, the aviation-derived gas generator, often considered too unusually complex mechanically, has been found to lend itself to normal maintenance techniques and skills consistent with high performance industrial machinery. The economics of how and where the reconditioning work is performed is determined by the user location and the quantity of gas generators involved. The "black-box" technique becomes more compelling as the site location becomes geographically remote and the environment becomes more hostile. The quick changeout feature permits maximum "on-stream" capability compared to conventional equipment, and has established unprecedented records for gas turbine availability.

APPLICATIONS

The acceptance of the jet gas turbines can best be substantiated by noting the number of manufacturers presently engaged in the various applications. Table 1 lists the gas generators presently in service in baseload applications.

In addition to the 413 units listed engaged in baseload applications, approximately 750 units are being utilized in marine applications and 1250 units in power generation (peaking) applications—a total of 2413 units for all applications.

Table 2 indicates application, uses, and geographical location of the various prime movers utilizing the gas generators listed in Table 1.

Gas transmission represents approximately 80% of the base-load horsepower installed. Basic reasons for selection of jet gas turbines by gas transmission users include:

1. **Favorable Installation Cost.** The equipment involved is of a size and weight that it can be packaged and tested as a complete unit within the manufacturer's plant. Generally, this will include the driven pipeline booster, all auxiliaries and control panels specified by the user. With the equipment thus matched and then debugged during testing, the package can be installed at the jobsite with less construction and startup effort than equipment that is matched for the first time at the jobsite.

2. **Adaptation to Remote Control.** Users strive to reduce operating costs by automation of their pipeline systems. All new stations today are designed for remote unattended operation of the compression equipment. Jet gas turbine equipment lends itself to automatic control as auxiliary systems are not complex, water cooling is not required (cooling by oil-to-air exchanges), and the starting device (gas expansion motor) requires little energy and is reliable. Safety devices and instrumentation adapt readily for purposes of remote control and monitoring the performance of the equipment.

3. **Maintenance Concept.** The off-site maintenance plan fits in well with these systems where minimum operating personnel and unattended stations are the objective. Technicians conduct minor running adjustments and perform instrument calibrations. Otherwise, the jet has turbine runs without inspection until monitoring equipment indicates distress or sudden performance change. Trend analysis equipment is being developed and installed and will serve to automatically scan instrumentation and to print out appropriate maintenance instructions and schedules. (see Figures 4 and 5)

TABLE 1. DATA ON GAS GENERATORS—BASE LOAD APPLICATIONS

Manufacturer	Model	ISO Rating, SHP	Thermal Efficiency-%	Power Turbine and Packaging Supplier	Base Load Applications	
					No. Sold	Hours Operation
Avco-Lycoming	TF25	2,250	22	A	4	28,900
Allison	501 K-13/16	4,000	27	DE/I	79	740,000
Cooper-Bessemer/ Rolls-Royce	RCT-30/Proteus	3,800	24	C	5	3,700
General Electric	LM100	1,150	21	I	13	375,000
	LM350	3,500	21	I	4	25,000
	LM1500	15,500	26	De/I/Dr	34	551,000
	LM2500	23,000	34	C/I	8	95,500
Orenda	OTF-370/390	8,900	22	O	25	540,000
Rolls-Royce	Avon 75/76	15,500	26	C/Dr/G/I	152	2,400,000
	Avon 101	18,200	28	C/I	10	70,100
	Avon 121	20,000	29	C	1	(1974 install)
	RB-211	26,000	34	C	1	(1974 install)
Pratt & Whitney Aircraft	GG12A	3,100	20	C	17	650,000
	GG3C	14,400	26	C/Dr/I	31	1,715,000
	GG4A	20,000	25	C/T/W	28	610,000
	GG4C	35,000	30	U	1	(1973 Install)
Totals					413	7,804,200

CODE: Power Turbine and/or Packaging Supplier (Prime Contractor)

A = Avco Lycoming
 C = Cooper Industries, Inc., Cooper-Bessemer Company
 De = DeLaval Turbine, Inc.—Deltex Division
 Dr = Dresser Industries—Gas Turbine Division
 G = GEC—English Electric
 I = Ingersoll-Rand Company, Turbo Products Division
 O = Orenda, Ltd.
 T = Turbo Power and Marine Systems
 U = United Aircraft of Canada
 W = Worthington Turbine International/Turbodyne Corporation

TABLE 2. JET GAS TURBINES IN BASE-LOAD APPLICATIONS

Application	Driven Equipment	Locations
Gas Transmission	Centrifugal Pipeline Boosters	U.S.A. Canada Netherlands West Germany United Kingdom
Gas Reinjection (Gas Conservation and Secondary Oil Recovery)	Natural Gas Centrifugal (Multi-stage) Compressors	Canada Venezuela Algeria Libya
Ammonia Production	Synthesis Gas Centrifugal (Multi-stage) Compressors Centrifugal Air Compressor	Australia Qatar
Helium Production	Centrifugal Compressor	U.S.A.
Power Generation, On-Site for Process Plant	Electric Generator	U.S.A. United Kingdom Libya Qatar
Oil Transmission	Centrifugal Oil Pumps	Venezuela Alaska (future)
Water Flood (Secondary Oil Recovery)	Water Injection Pumps	Venezuela Libya
Gas Regeneration	None-Exhaust gas ducted to catalyst regenerator	U.S.A.

Oil transmission has the same general characteristics as the gas transmission applications noted above. A future installation of jet gas turbines involves the proposed 800 mile oil pipeline across Alaska. An interesting design feature of the prime mover package (13,500 SHP rating) is that space and weight envelopes permit it to

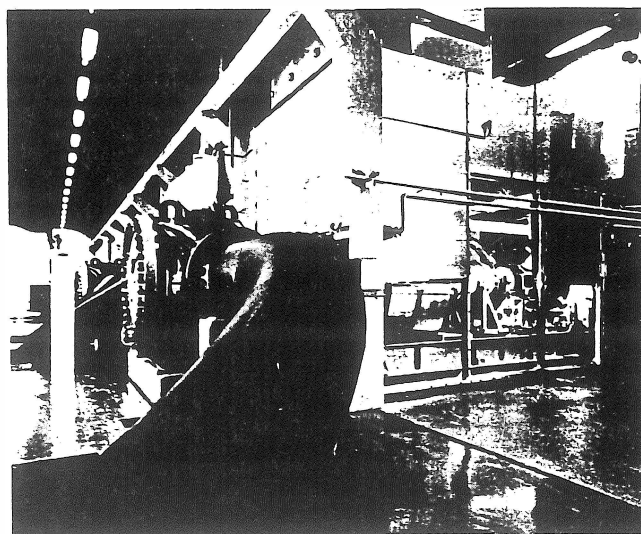


Figure 4. SHP jet gas turbine driving pipeline booster in Netherlands gas transmission station. Acoustical panels reduce sound levels within compressor building.

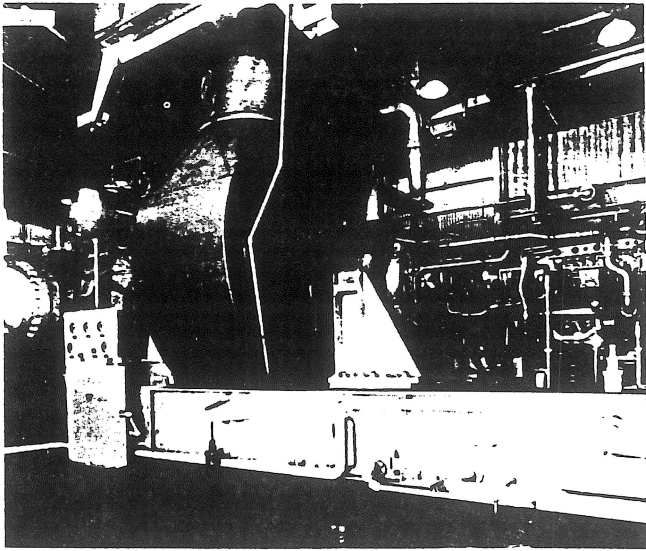


Figure 5. 20,000 SHP unit in gas transmission service. Gas generator is a derivative of CF-6 aircraft engine.

be air-lifted by Lockheed Hercules, if logistics require this mode of transportation (see Fig. 8)

Gas reinjection (including gas lift) and *water flood* applications are characterized by their geographically remote locations at sites of large oil field discoveries. The plants are normally designed for local operation as the compression process is not system integrated as in a long distance pipeline. The jet gas turbine maintenance concept is attractive in that minimum maintenance personnel and minimum inventory requirements blend well with the isolated plant sites. In the case of gas lift plants in Venezuela, compression units are singly located on offshore platforms (with no quarters for personnel) and crew boats provide the only method of transportation. (see Figure 6)

Ammonia production, helium production, and on-site power generation have similar requirements. In particular, the value of the process product is very high and "on-stream" availability is paramount. In about all cases, the gas turbine exhaust gas heat content is ducted to a "waste heat" exchanger where the exhaust energy is converted to a useful process requirement—to generate steam

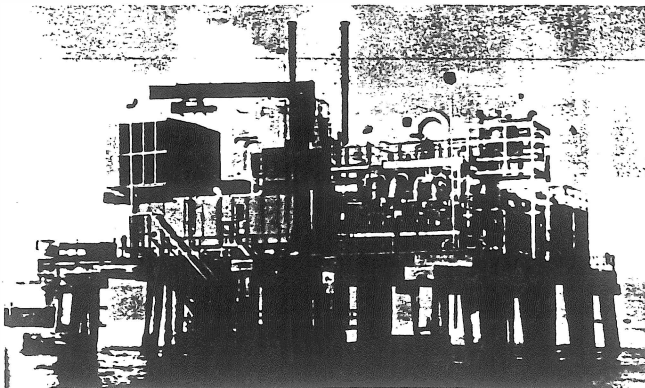


Figure 6. 12,500 SHP jet gas turbine driving compressors in gas lift service on Lake Maracaibo.

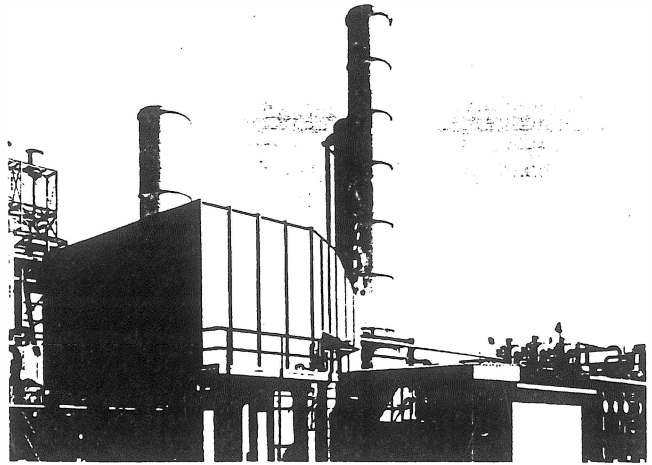


Figure 7. Ammonia production plant in Australia with 16,000 SHP unit driving three synthesis gas compressors L to R: Air filter and inlet system, gas turbine inside acoustic cab, control panels inside masonry structure. In background is waste heat boiler generating steam from gas turbine exhaust energy.

or heat process oil as examples. As a result, the gas turbine is credited with the process cycle efficiency increase and can become a key economic factor in the choice of equipment. (see Fig. 7)

Gas regeneration is an application wherein no mechanical horsepower is developed. The gas generator exhaust gas is ducted directly to a regenerator wherein the heat energy is added to a catalyst bed for the production of butadiene.

There are several interesting subjects worth noting that are receiving considerable attention and which are common to all base-load applications today.

Air Handling—Installations today are extremely diverse; from arctic to desert to off-shore platforms. Each is unique with respect to techniques to handle the air to prevent erosion or corrosion to the front-end blading of a gas turbine axial compressor. Air filtration and inlet

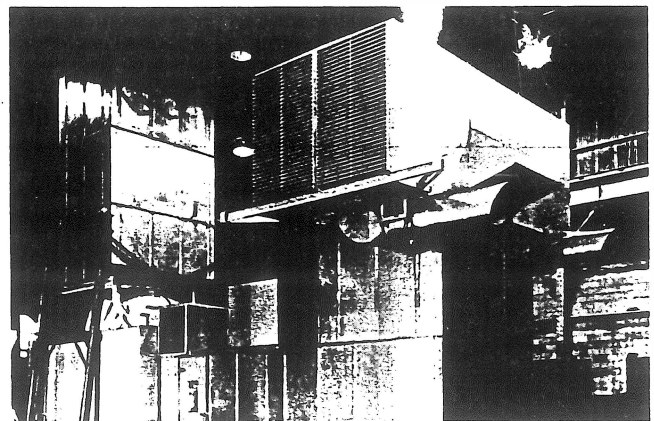


Figure 8. 13,500 SHP Prime Mover for Oil Transmission service fully assembled for factory testing. Unit is modularized for air transport to Arctic station sites, if logistics require.

systems are being "customized" increasingly to fit a particular environmental, rather than the general-purpose designs of the past.

In the winter climate installations, where near-freezing conditions are prevalent, methods had to be developed to prevent the formation of ice in inlet systems to avoid the possibility of ice ingestion. Where environmental pollutants cause performance deterioration to an axial compressor, various different cleaning techniques have been developed and evaluated to restore performance with the unit remaining in operation.

Noise—Like all equipment and machinery today, the jet gas turbine must be a good neighbor. To the surprise of the uninitiated, these units are relatively easy to silence with the use of external inlet and exhaust silencers and acoustical enclosures. There are many examples where the overall noise level of gas turbine equipment has been reduced to meet residential criteria. In addition to the gas turbine itself, attention must be given to radiator and ventilation fans, air filter blowers, and auxiliary pumps when designing for very low ambient noise installations. As the tradeoff to noise reduction is increased cost and construction effort plus higher pressure drop (decrease in available SHP), the user should select a design criteria consistent with local ambient conditions or regulations to avoid over-complex designs.

Appearance—Increasing emphasis placed on plant design is the requirement for a pleasing appearance. Package suppliers frequently provide the filters, silencers, and enclosures for jet gas turbine equipment so a variety of materials, colors, and configurations have emerged to meet the individual requirements.

FUTURE TRENDS

Observing the performance and experience record accumulated in the past ten years, the jet gas turbine industry is more optimistic than ever in its ability to meet market requirements of all varieties. As the aviation-derived gas generator continues to serve the base-load applications, the models involved will continue to improve durability-wise. The high-time unit just achieved 33,558 hours (4 years of operation) without requiring reconditioning. The ultimate lifespan is unknown at this point and only further operating experience will resolve the question. New models are being introduced, the most significant of which are the new generation of engines for heavy transport aircraft. These engines feature fuel savings of 30% over previous designs, due to high temperature/pressure cycle designs and improvement in materials and material cooling techniques. The LM2500 gas generator, a derivative of the CF6 and TF39 aircraft engines, has been in gas transmission service for nearly three years. The first industrialized RB-211 will be placed into gas transmission service in October, 1974. The JT9, CF6-50, Olympus 593, Spey, and M-45 aircraft engines are similar state-of-the-art engines and are expected to be introduced to industrial applications in the future.

Certain models of gas generators, having entrenched themselves in ground-based service, are now spawning variants which will never see aviation service. The Avon 76, as an example, has spun off the Avon 101 (maxi-Avon) which raises the SHP by 18% and lowers the fuel rate by 7%. The uprating is accomplished through the introduction of a higher temperature cycle plus air-cooled first stage turbine blades. Another spin-off, the Avon 121 (maxi maxi-Avon) will be introduced shortly which will raise the Avon 101 power level by 10% and the fuel rate by 3%.

The Pratt and Whitney GG4A has spawned the GG4C which features an additional axial compressor stage plus turbine-end modifications to permit higher temperature cycles. These variants were developed and justified on industrial forecast only and will remain unique to ground-based applications.

Another trend becoming evident is the pooling of industrial and aircraft technologies in the development of future gas generators. Several companies have formed joint ventures or cross-license arrangement to exploit this opportunity for future industrial activity.

Future industrial gas generators will continue to utilize the advanced metal technology, component design, and manufacturing techniques as it becomes available from the aviation industry. As a result, more efficient simple cycle designs will become available that are competitive with present regenerative cycle gas turbines. Throughout these new developments, it is expected that gas generators will continue as separable compact assemblies in order that the quick changeout maintenance technique will be retained.

SUMMARY

The jet gas turbine has established itself as a viable and competitive product in the marketplace. The technology and practices evolved within the aircraft industry have had a major impact in the successful development and application of this product as a reliable industrial prime mover. In particular, the maintenance concept has proved to be of economic benefit to the base-load industrial user.

Future opportunities are optimistic in that improved and more efficient designs will become available which will combine the best of skills and technologies from both aircraft and industrial resources.

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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 300 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 designed 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

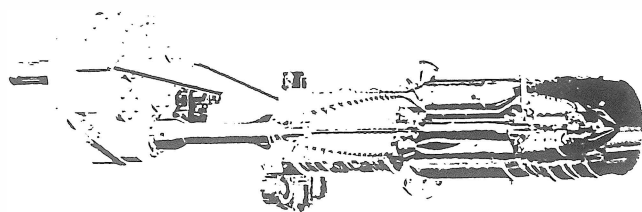


Figure 1. Model T56-A-15 Turboprop Engine. Application C-130.

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).

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.

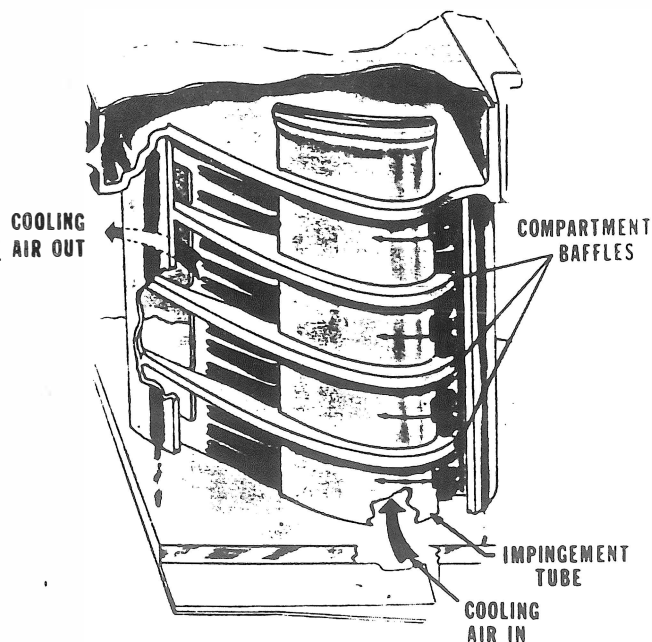


Figure 2. Vane Cooling Schematic.

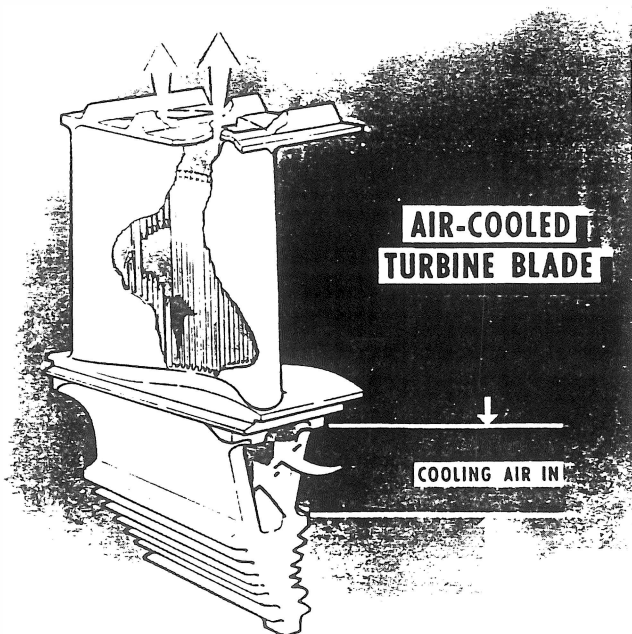


Figure 3. Air-Cooled Turbine Blade.

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 Lockheed 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 air-

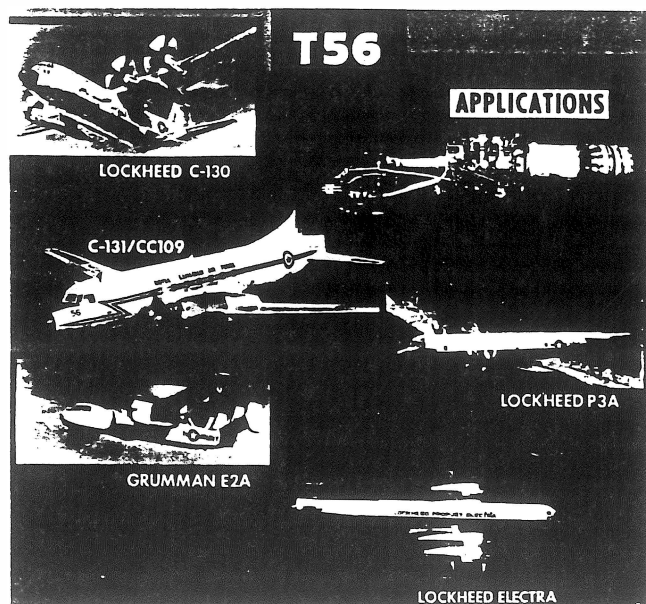


Figure 4. T-56 Applications.

craft 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.

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 section 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 $\frac{1}{2}$ ".

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,

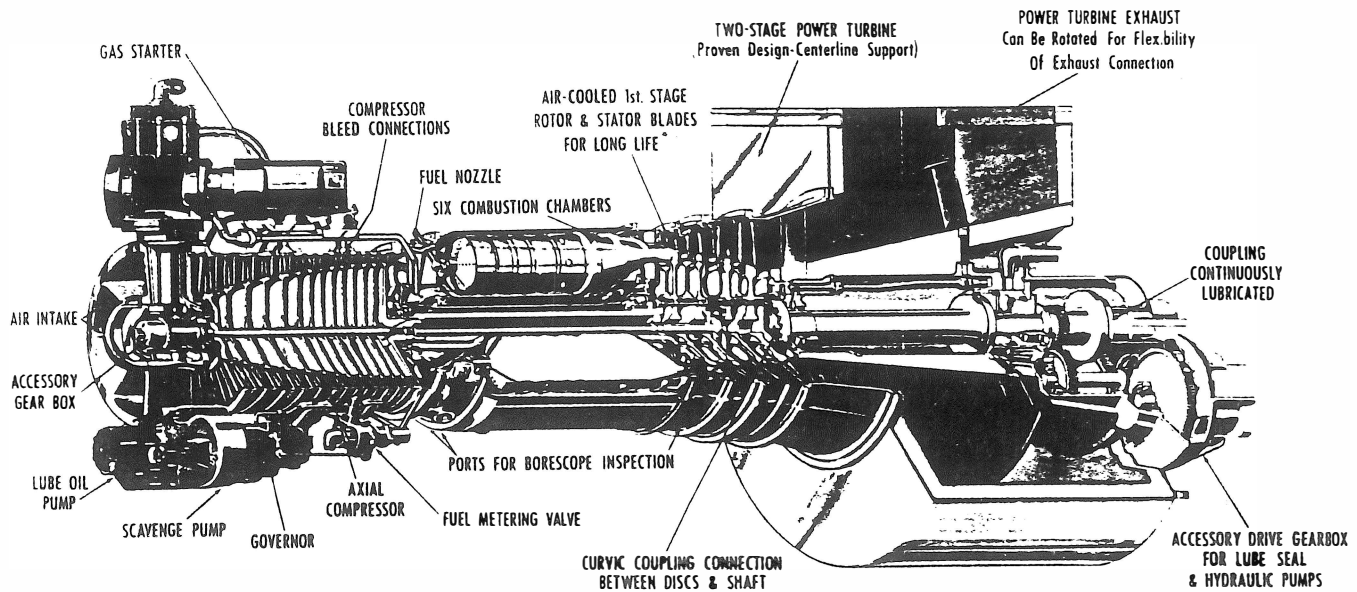


Figure 5. GT-40 Gas Turbine.

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 auxiliary 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

501-K16 GAS GENERATOR

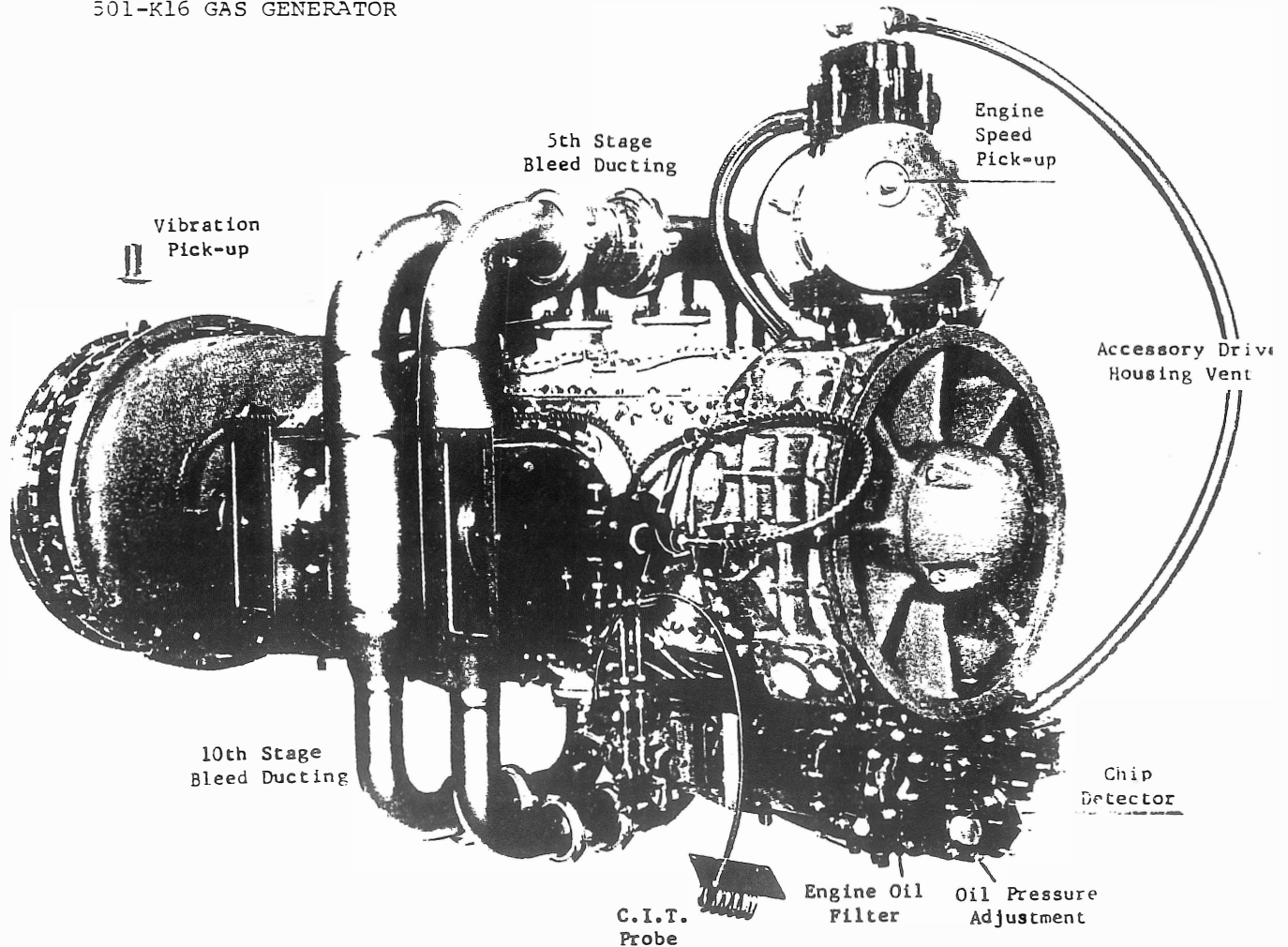


Figure 7. 501-K16 Gas Generator.

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 manu-

facturer 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

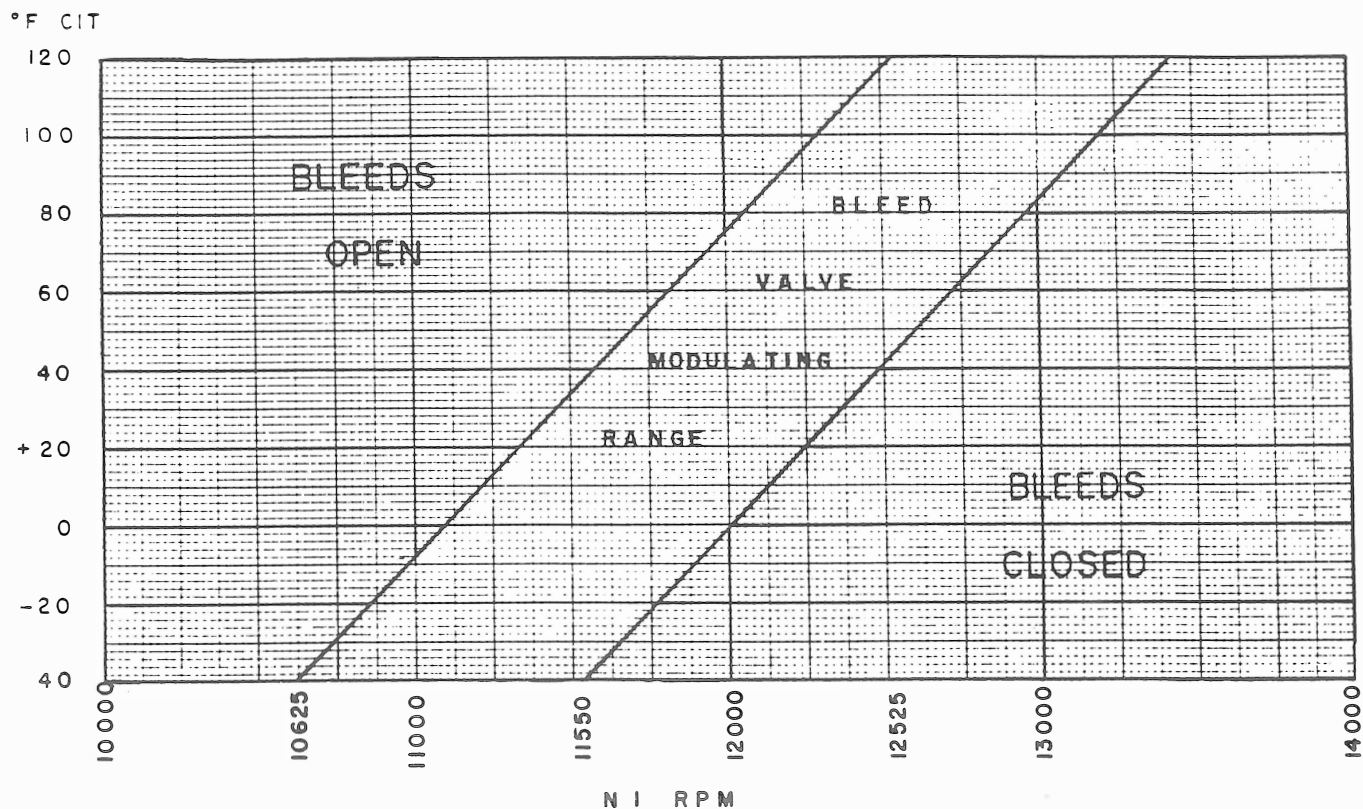


Figure 3. 501-K16A Engine—Acceleration Bleed System Actuating Range.

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.

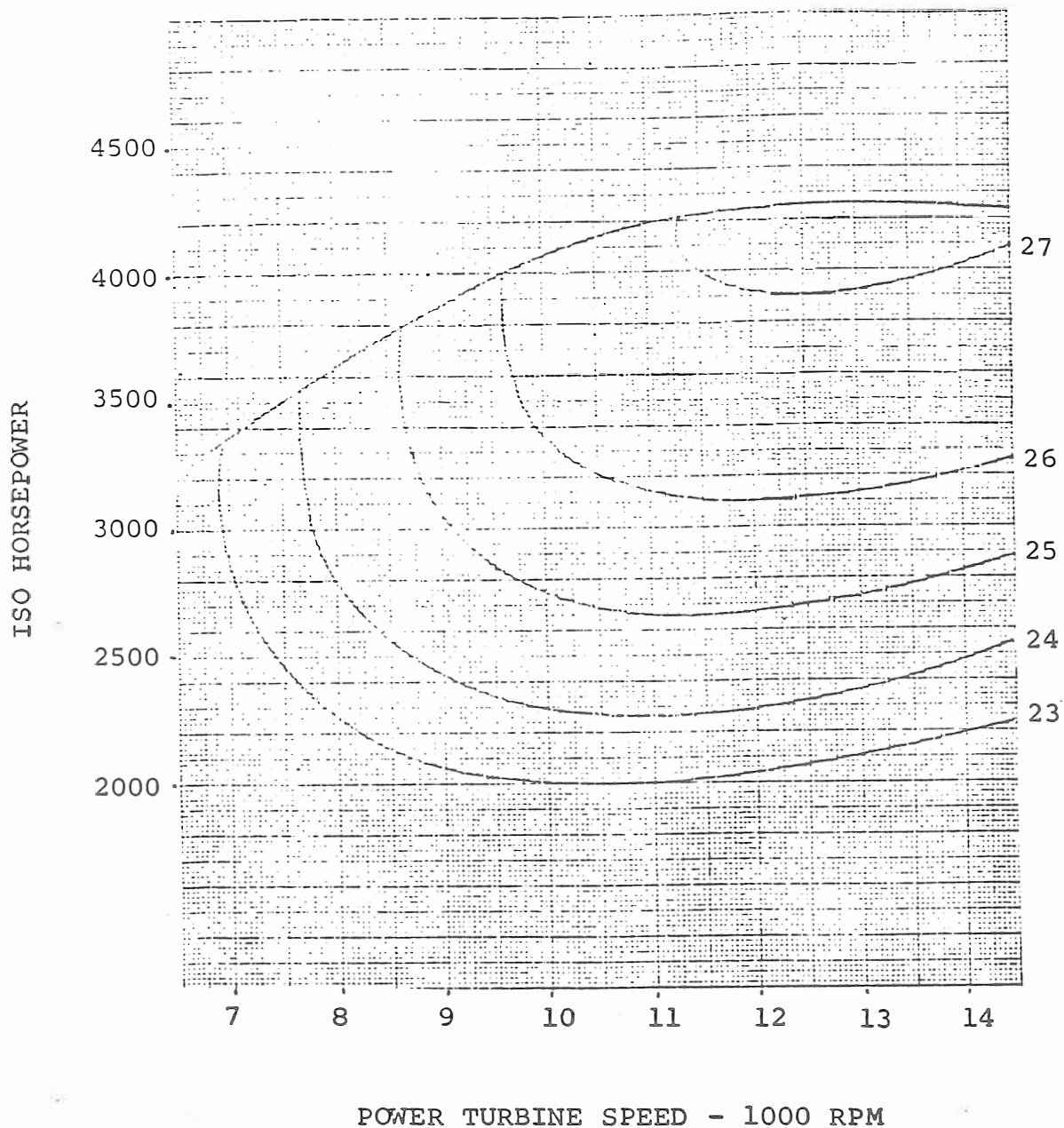


Figure 9. GT-40 Gas Turbine. ISO Performance (60°F at Sea Level). TIT = 1800°F.

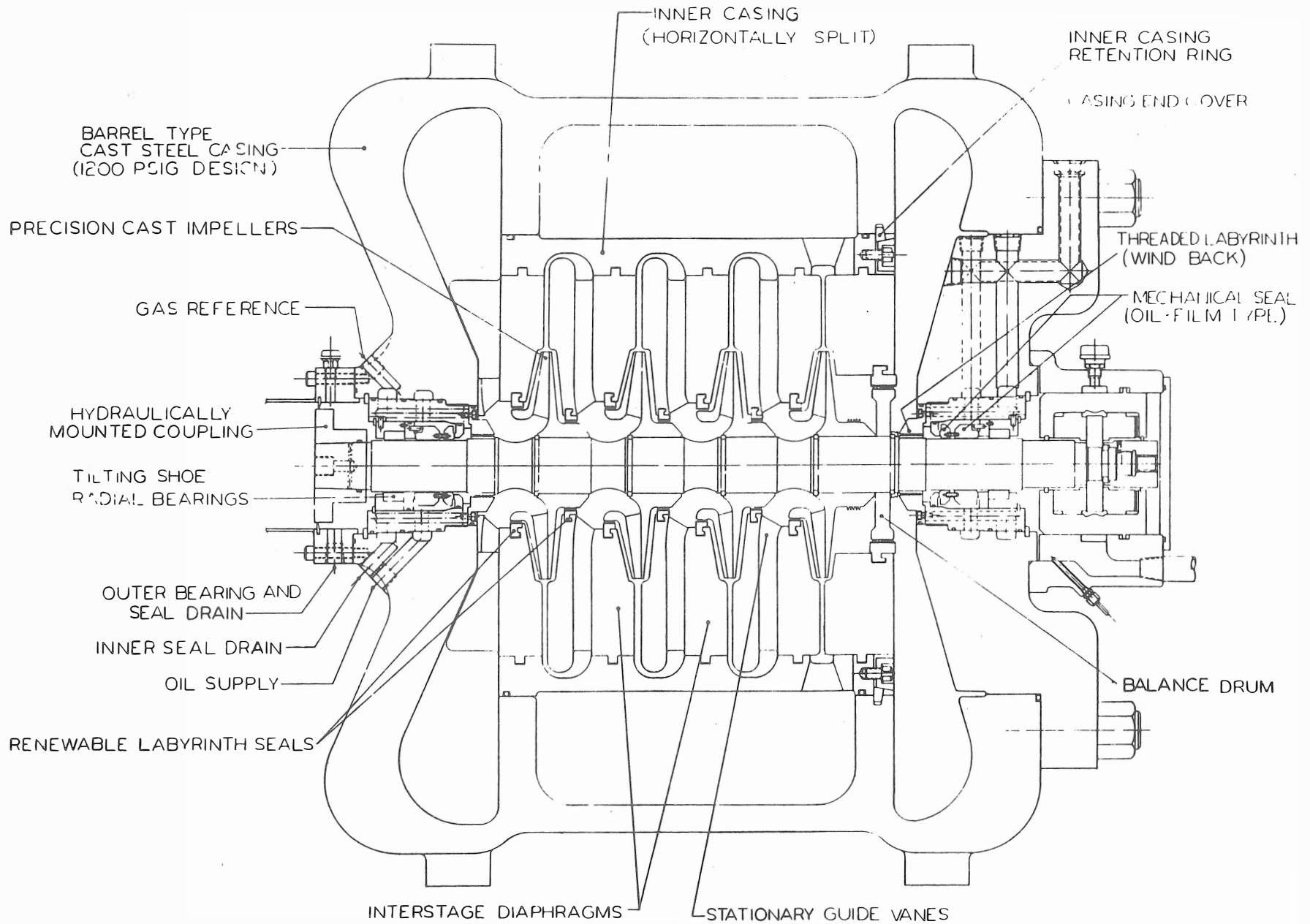
Exhaust silencing can be provided to meet various noise requirements as specified. The package configuration includes a support structure for the exhaust when needed.

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)



CONVERSION OF A SINGLE-SHAFT TURBOPROP ENGINE

Figure 10. CDP-416 Compressor Assembly.

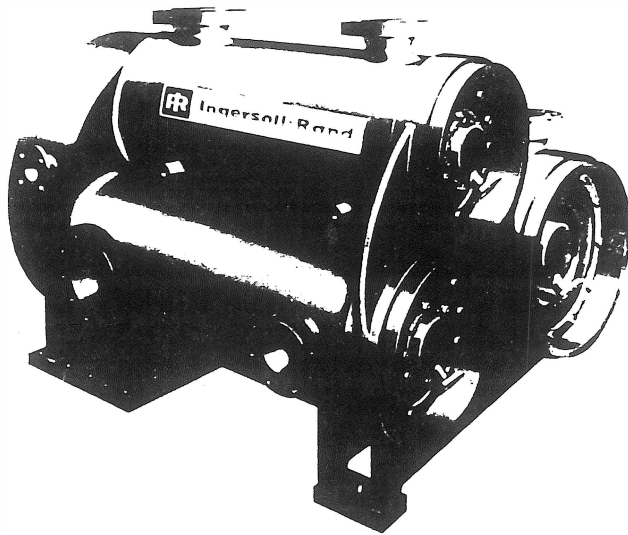


Figure 11. Centregal Compressor.

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

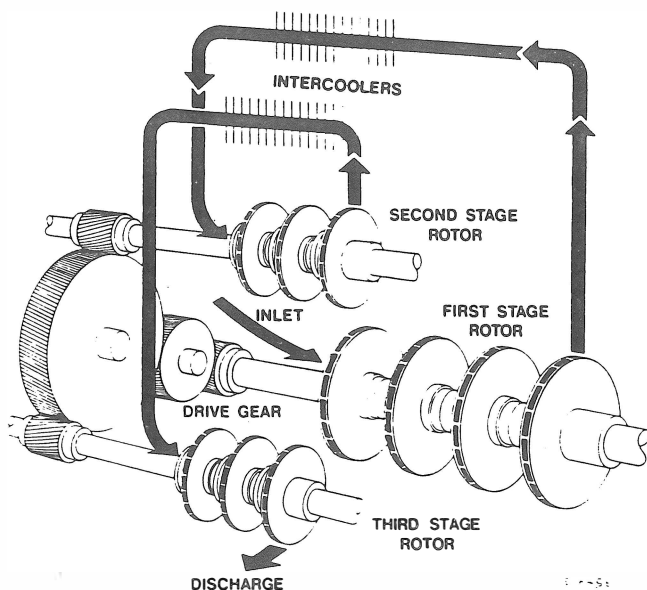


Figure 12. Centregal Compressor Flow Schematic.

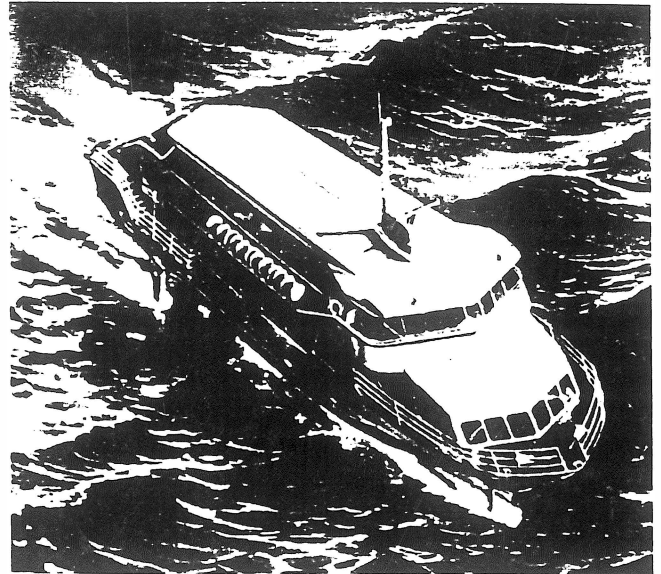


Figure 13. New 250-passenger Hydrofoil Designed by Boeing Company.

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.