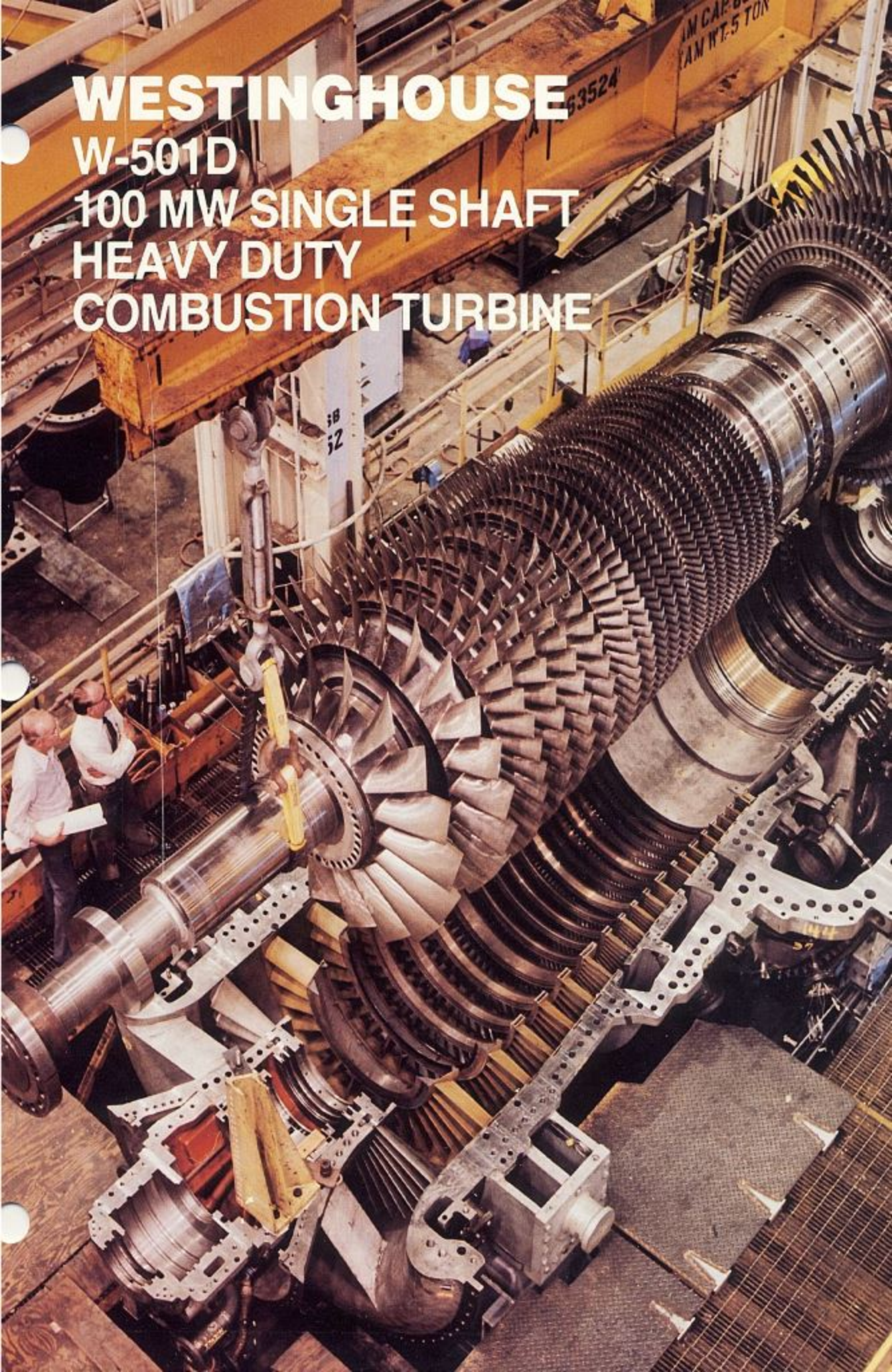
WESTINGHOUSE
W-501D
100 MW SINGLE SHAFT HEAVY DUTY COMBUSTION TURBINE



Westinghouse Combustion Turbine Systems

The Ready Source of power

FRONT COVER

A Westinghouse W-501D combustion turbine rotor being lowered into the cylinder base in the factory at Lester, Pennsylvania, USA.
The use of horizontal cylinder joints provides access to the rotor at the purchaser's site.

The Westinghouse 100 MW combustion turbine

by A J Scalzo, G S Howard, P C Holden, J Morrash,
Westinghouse Combustion Turbine Systems Division

The Westinghouse W501 combustion turbine has evolved from a 30 MW, 25 per cent efficient plant to a present level of 100 MW and 33 per cent. With a focus on reliability, the basic features of the current model are designs which have been proven in the course of this evolutionary process. The W501D has been in production for over five years with little change in turbine inlet temperature. Performance gains have been obtained from improvements in component efficiency, basic matching of components and conservation of cooling air. The engine and plant have been designed for maximum application flexibility and maintainability.

For more than 20 years Westinghouse single shaft, two bearing, direct drive combustion turbine power plants for simple and combined cycle applications have undergone continuous evolution. When first introduced in 1960, the power rating was approximately 30 MW with a plant efficiency of 25 per cent. The present 100 MW class W501D production unit has an efficiency in the 33 per cent range. There are over 180 of these large direct drive units in operation, including 19 in combined cycle PACE applications, burning fuels ranging from natural gas to residual oils. Over two million operating hours have been accumulated on these machines.

The Westinghouse evolutionary design process has maximum reliability as its major objective. Therefore, many basic features proven reliable over the years have been retained in addition to the 7.2 metre span, two bearing rotor concept. Most noteworthy of these are the CURVIC coupled turbine discs, tangential exhaust bearing struts, blades and stationary vanes which are field removable with the rotor in place, and a compressor end drive.

The latest engine model, W501D, has been in production for over five years with little change in turbine inlet temperature. During this time, the progress made in cooling and mechanical design technology has been focused on improved reliability. Performance gains have been obtained from improvements in component efficiency, basic matching of components and from conservation in the management of cooling air.

Evolution

The W501 genealogy begins with the 30 MW W301, which began commercial operation in 1960. Unlike previous, smaller, higher speed engines the W301 was directly connected to the generator without a gear. W301 features which are still retained in the W501D include:

- Horizontally split casings;
- Two bearing rotor;
- Compressor rotor with shrunk-on discs;
- Turbine rotor with bolted, CURVIC coupled discs;
- Compressor diaphragms removable in situ;
- Dove-tail compressor blade roots that facilitate in situ blade removal;
- Fir-tree turbine blade roots that facilitate in situ blade removal;
- Multiple combustors to facilitate full scale lab testing;
- Tangential exhaust casing struts to maintain rotor alignment;
- Cold end generator drive to eliminate the need for a flexible coupling.

Table 1 traces the development of the W501 family from the W501A to the current W501D model. The W501A was designed to meet a 45 MW need by utilising the proven, high performance W301 compressor, with an added front and aft stage to increase the air flow and pressure ratio, and a newly designed four stage turbine. In addition, the W501A introduced the following improvements;

- Variable inlet guide vane to provide exhaust temperature control on heat recovery applications and to improve starting characteristics;
- Multiple blade ring concept with a roll-out feature to provide field service of stators with rotor in place;
- Precision cast stator vane segments;
- Cooled Row 1 vane segment;
- Segmented outer shrouds opposite rotor blades to provide free thermal expansion;
- Four-pad, tilting pad bearings to eliminate any possibility of bearing instability from oil whip phenomenon.

The 60 MW W501AA used a newly designed, higher flow, higher pressure ratio compressor with the W501A turbine at essentially the same firing temperature. Another major design change was a reduction in combustor shell diameter in order to facilitate shipping the engine fully assembled, a feature which has been retained on subsequent models.

The 80 MW W501B was a planned growth step with the principal change being an increase in turbine inlet temperature. In addition to increased Row 1 vane cooling, cooling was added to the Row 1 blade and Row 2 vane and material was changed as required on other rows to compensate for higher gas temperatures. Provision was added for removal of both combustors and transition pieces without a cover lift.

The 95 MW W501D was a continuation of the planned growth programme for the W501 frame. A further increase in turbine inlet temperature above the W501B was made possible by advances realised in turbine cooling technology. Two stages were added to the aft end of the W501B compressor for higher pressure ratio in order to optimise efficiency in simple and combined cycle operations. Cooling was added to the Row 2 turbine blade along with increased cooling in upstream stages and material changes as required.

The current W501D achieves additional performance gains from improvements in component efficiencies and from conservation of cooling air energy with very little change in turbine inlet temperature. Compressor performance is improved by increasing the number of diaphragm seal points from two to four and by use of coated diaphragms with improved surface finish to retard degradation from ingested contaminants. Turbine performance is improved by reducing exit velocity and swirl, by reducing incidence losses, and by better stage work distribution. Stator cooling air is extracted from three compressor bleed points in order to use air at the lowest suitable pressure available. Improvement in detail design has reduced internal cooling flow leakage by 12 per cent compared to the earlier W501D.

Other features provide improved reliability and availability by virtue of improvement in parts life and easier maintenance and inspection. In the compressor, the aerofoil-shroud joint has been redesigned for increased strength in key diaphragm stages. Also, the four-point diaphragm seal construction provides improved rigidity. A provision has been added to verify concentricity of the compressor rotor with the casing during manufacture and for use during service for diagnostic purposes. Ports are available for borescope inspection of both compressor and turbine blading. In the turbine, single Row 1 vane segment construction permits replacement without a cover lift and also reduces vane-shroud junction stresses.

Engine description

The improved performance W501D currently in production, shown in Figure 1, is characterised by industrial-type construction, as were all its predecessors. All casings are horizontally split to facilitate field maintenance with the rotor in place. The single shaft rotor is made up of the compressor and

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turbine components joined by a centre coupling. The 19 stage compressor rotor is a single forging with discs shrunk on. The turbine rotor is made up of discs which are bolted together using CURVIC couplings, which consist of toothed connection arms that extend from adjacent discs and interlock when the discs are bolted together. Each rotor component is balanced separately before the marriage at the centre coupling. A final full spindle balance is then performed before assembly into the casing. The two main journal bearings are of the inherently stable, tilting pad type, designed and developed by Westinghouse. The thrust bearing is a Kingsbury double acting tilting shoe type.

The inlet system delivers air to the compressor via a bellmouth. The compressor is of a highly efficient 19 stage design with light aerodynamic loading. Pressure ratio is 14/1. The inlet guide vanes are variable to facilitate starting and to control exhaust temperature for heat recovery applications. Three axi-symmetric bleeds, which can be seen in Figure 2, are incorporated in stages 6, 11 and 14. These are used to provide cooling air for turbine stages 4, 3 and 2, respectively. The 6th and 11th stage bleeds are also used to avoid surge during starting. The compressor rotating blades incorporate pinned half ball type roots to facilitate field replacement. Labyrinth type four point seals are used to minimise leakage past stationary rows. Coatings are applied to all diaphragms to improve compressor performance and to retard compressor performance degradation due to fouling.

The combustion system incorporates 14 combustors, reduced from 16 on earlier W501s, each supplying a transition duct that directs combustion gases into the turbine. An extended lip combustor wall construction has been utilised to provide improved cooling. Ignition is provided by spark plugs in two combustors, one of which is redundant for reliability. Cross-flame tubes are provided to propagate flame to those combustors which do not contain spark plugs. A combustor, transition piece, and cross-flame tube can be seen in Figure 3. The atomisation provided by the pressure atomising liquid fuel nozzles is assisted during early phases of starting by the use of atomising air supplied by an auxiliary blower.

With a larger head end diameter than on previous W501s, the combustors are designed to accommodate low Btu gas as well as natural gas and liquid fuels ranging from light naphtha to residual oil. The presence or absence of flame and the uniformity of distribution of fuel flow between combustors are monitored by thermocouples located downstream of the last stage turbine blades. These can also detect combustor malfunctions.

The four stage, air cooled turbine is designed with modest aerodynamic loading and reaction to provide high efficiency. Good performance is also promoted by low last stage leaving velocity energy. The four rows of cast stationary vane segments (see Figure 4) are supported in individual blade rings. These also support investment-cast ring segments which form the outer shroud over the rotating blades and serve to isolate the blade rings from hot blade path gases.

The interstage labyrinth seals, which minimise the leakage flow through the rotor/stator clearances between turbine stages 2, 3 and 4, are housed in rings that are supported from the vane segments by centrally located, radially orientated keys. This construction permits the seal rings to expand independently of the blade rings and vane segments during transients and avoids excessive running clearances during steady-state operation, thus maximising efficiency. Leakage past the Row 1 vane segment inner shroud is minimised by the use of spring loaded seal segments which accommodate relative thermal growth without clearance increases.

The turbine cooling system is shown in Figure 5. Compressor discharge air is bled from the combustor shell and directed to an air-to-air cooler and filter prior to being supplied to the rotor for cooling purposes.

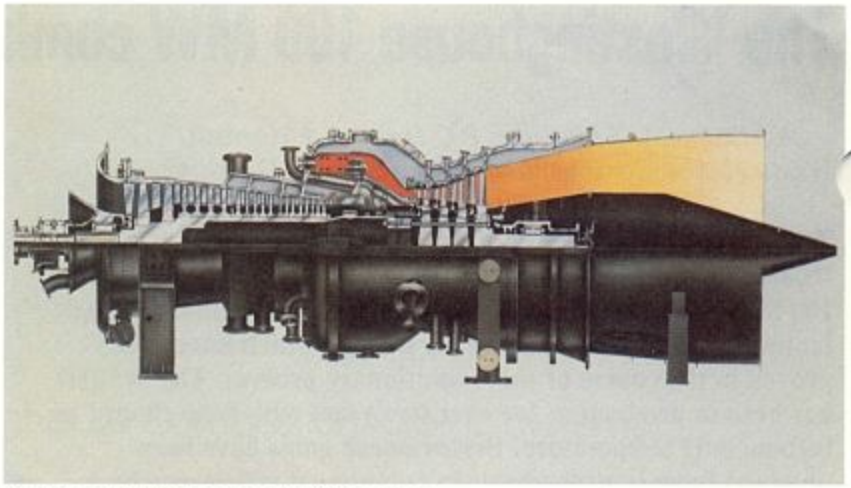


Figure 1. Longitudinal section of W501D engine

Table 1. W501 evolution

Frame	W301	W501A	W501AA	W501B	W501D	
First startup date	1960	1968	1971	1973	1975	
					Initial	Current
Power — MW class	30	45	60	80	95	100
Turbine inlet temperature — °F	1450	1620	1635	1810	2005	1985
Turbine inlet temperature — °C	788	882	890	988	1096	1085
Airflow — kg/s	201	249	338	339	355	355
Bearing span — m	7.24	7.24	7.24	7.24	7.24	7.24
Number of compressor stages	15	17	17	17	19	19
Number of turbine stages	4	4	4	4	4	4
Number of cooled turbine rows	0	1	1	3	4	4

Figure 2. Compressor cylinder

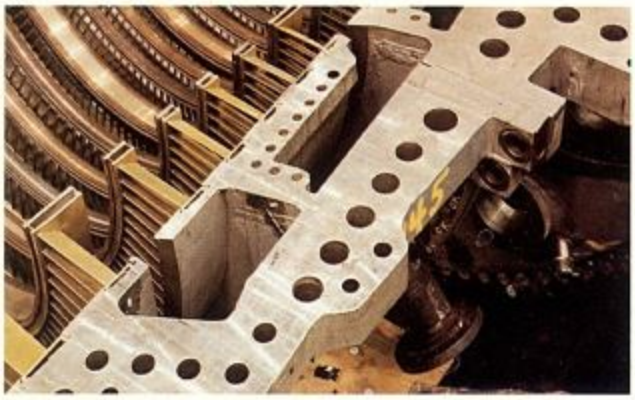
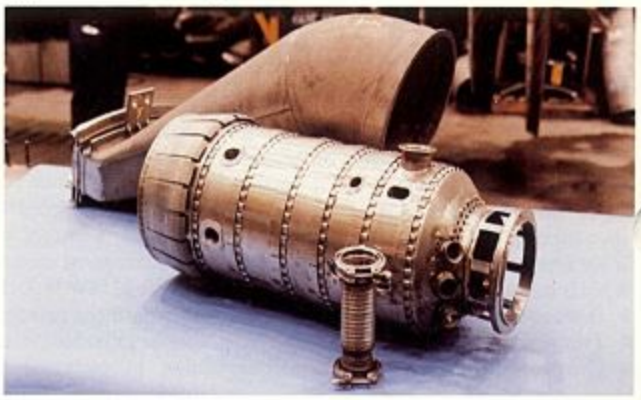


Figure 3. Combustion system hardware



Besides being used for cooling the Row 1 and 2 blades, this air provides a cool environment for the entire turbine rotor and serves to provide cooling for the discs. The turbine blades have extended necks to aid in isolating the disc rim and blade roots from hot blade path gases. Cooling air is transmitted through the Row 2, 3 and 4 vane segments to supply the interstage seal leakage requirements. This serves to keep the rotor seal arms cool. The Row 1 and 2 turbine blades are cooled with spanwise holes which are supplied with coolant from cavities formed by the blades and bottom disc serrations. The holes exhaust at the blade tips, as can be seen on Figure 6. The Row 1 and 2 vane segments are cooled using impingement type inserts.

The exhaust cylinder houses the exhaust end bearing and utilises six equally spaced tangential struts to support the bearing housing. Aerofoil shaped covers protect the support struts from the blade path gases and support the inner and outer diffuser cones. The tangential support struts are thus permitted to achieve steady-state temperature slowly during transients while maintaining precise alignment of the bearing housing by rotating the housing as required to accommodate differential expansions.

The exhaust transition incorporates two large, aerofoil shaped access ports to provide support for the inner wall and access to balance planes when required. The exhaust bearing cavity is ventilated by air drawn in through the access ports by the aspirating action of the turbine flow path, which maintains a sub-atmospheric pressure at the turbine exit. The unique turbine diffuser-axial exhaust system is highly efficient in reducing the turbine leaving loss by allowing a large reduction in exhaust gas velocity before it enters the stack or heat recovery boiler.

Fuel flexibility

The ability to burn a wide range of fuels has been inherent in Westinghouse combustion turbines from their inception, and wide operating experience has been gained on fuels ranging from residual oil to low Btu gas. Most fuels can be accommodated in the W501D with standard hardware. However, some liquid fuel properties require special consideration in the fuel delivery system. Residual oils require heating to maintain suitably low viscosity, and startup and shutdown is accomplished on distillate oil or natural gas. Lubricity additives could be required for light fuels to aid pumping. Vanadium, alkali metal and other impurities in fuels must be held below prescribed limits to avoid corrosion of turbine parts. Washing apparatus can be added to the system for removal of sodium and potassium. Magnesium-containing additives are added to the fuel to inhibit vanadium.

Combustion tests have been run in the laboratory on full scale hardware with very low Btu gases such as are provided with some coal gasification processes. These show that depending on the fuel properties it may be necessary to start the engine on distillate oil or natural gas and switch over to the low Btu gas at part load. Low Btu gas applications require fuel nozzle modification to pass the increased volumetric flow. With some low Btu gases, combustor modification may also be required. The combustor head end design of the W501D anticipates any changes that will be required.

Inspection and maintenance features

The W501D engine is designed and built for ease of maintenance and inspection. It is located in a roomy enclosure with a walkway on one side and laydown space on the other. Any maintenance and inspection which does not require engine cover removal is conducted without disruption of the enclosure with the work performed in a weather protected environment. The engine cover consists of several independently removable sections for easy engine access. The enclosure roof is also sectionalised. When an engine cover section must be removed, only that portion of the enclosure roof immediately above it need be removed.

Westinghouse maximises the number of maintenance and inspection operations that can be made without engine cover removal. For example, a visual examination of the compressor and turbine blading is now provided to a large extent without lifting covers. Borescope ports are located at key positions in both the compressor and turbine. Manways are provided in the exhaust and

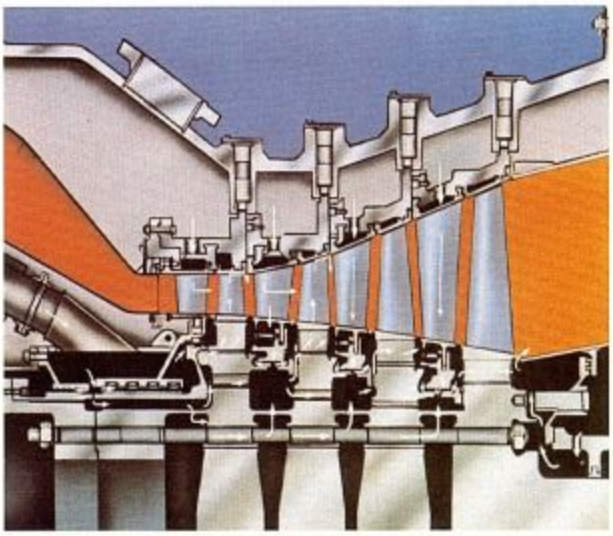


Figure 5. Turbine cooling system

Figure 4. Row 1 and 2 turbine vane segments

Figure 6. Row 1 and 2 turbine rotor blades

inlet which allow viewing the blade path components at either end of the engine. In addition, a man can gain access to the combustor section of the engine to examine the discharge end of the compressor and the inlet end of the turbine.

Two manways are provided in the cylinder for access to the combustor section. Combustors and combustor transitions are easily removed and replaced through these openings. The first stage turbine single vane segments can be replaced through the same manways.

Fuel nozzle maintenance is an external operation, as is field balancing. Normally, only two-plane balancing is required. These balance planes, at the inlet and exhaust ends, are conveniently accessible through plugged openings designed for that purpose. If a centre plane balance is required, this plane is externally accessible through the combustor section.

When covers must be removed, every consideration is given to reducing down time. Turbine and compressor blading can be removed and replaced without the necessity of rotor removal and without disturbing other blading. The blade rings carrying the turbine vanes are rolled in and out to service turbine stationary parts downstream of the Row 1 vanes.

The journal bearings and thrust bearing can also be removed without rotor removal. The two-bearing rotor construction makes the journal bearing easily removable at either end of the engine using a specially designed trolley assembly. The compressor end journal and the thrust bearing can be removed without lifting a cover. The exhaust end journal bearing can be removed by lifting the upper half of the exhaust manifold and the associated roof panels. However, this bearing can be inspected without exhaust manifold removal.

Econopac

The Westinghouse ECONOPAC, shown in Figure 7, is a simple cycle arrangement of plant apparatus including the engine, inlet and exhaust systems, generator and plant auxiliary equipment. The inlet air duct is located on the side of the combustion turbine. Located in the duct are trash screens and a silencer for sound attenuation.

In ECONOPAC installations the exhaust gases leaving the diffuser pass through a transition to the base of the vertical exhaust stack. The gases are guided through a 90° turn at constant velocity into silencer panels and are discharged to the atmosphere. In combined cycle applications, the gases pass through the exhaust heat recovery system before entering the stack.

The generator, shown in Figure 8, is an outdoor, hydrogen cooled, two pole, ac synchronous type with a brushless exciter. A permanent magnet generator provides power to the voltage regulator which controls the stationary field of the exciter. The ac exciter field produces current in the exciter armature, the output of which is rectified by silicon diodes mounted on the shaft. The resulting direct current is carried through leads in the shaft to the rotating field of the generator, which produces a three-phase output in the generator armature.

Continuous circulation of hydrogen coolant through the generator air gap and over the rotor and stator conductors is maintained by shaft mounted blowers. Hydrogen coolers are located within the generator frame which reject heat through a glycol cooling loop and a glycol-to-air cooler located on the roof of the ECONOPAC.

The plant auxiliary equipment is prepackaged to the maximum extent possible and is located in three enclosed packages.

The starting package contains the electric starting motor with its associated torque converter, step-up gear, and clutch. Also housed in the starting package is the turning gear, which is engaged during engine cool-down to prevent rotor warpage due to uneven cooling, and the blower which provides air to assist in atomising liquid fuel during starting.

The engine control and monitoring equipment is housed within the electrical/control package. Close attention is paid to providing a good environment for this equipment. No mechanical components are included in the

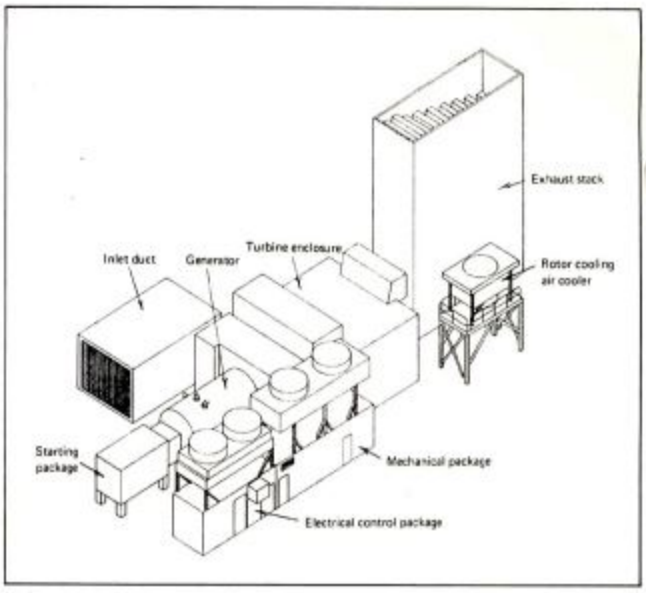


Figure 7. W501D ECONOPAC schematic

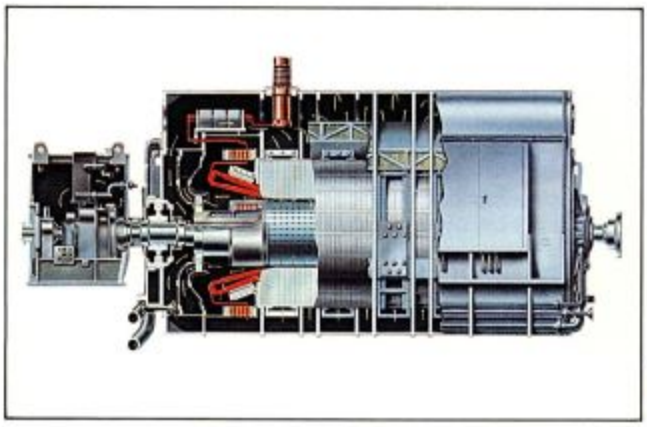


Figure 8. 3600 rpm hydrogen cooled generator

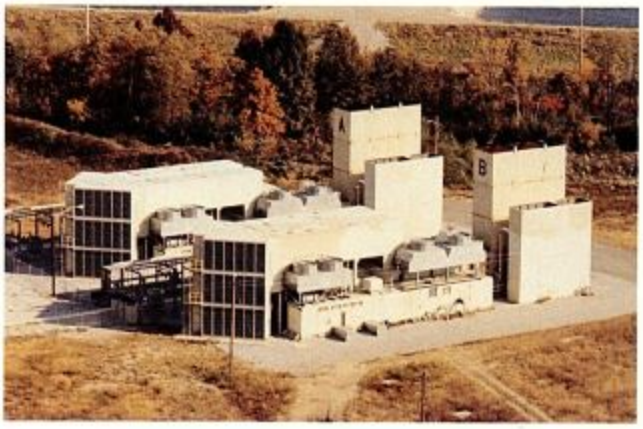


Figure 9. Enclosed two unit ECONOPAC installation

enclosure, which eliminates a major source of environmental contamination, and the enclosure is air conditioned. The power-logic control system provides the operator with one-button, automatic start-up from a cold condition to a pre-selected load. This is accomplished with proven solid-state electronics in the control and monitoring system and field tested electro-mechanical relays in the sequencing system. All the hardware used has wide use in power plants and is readily understood by qualified utility maintenance personnel.

Redundancy has been provided in those areas where experience has indicated that by so doing plant availability is enhanced. The nucleus of the system is the analogue control, which automatically schedules the fuel flow during combustion turbine acceleration and loading and provides closed loop control of speed, megawatts and cycle temperature during steady-state operation. The all-electronic fuel control reacts promptly to changes in input to enhance the reliability and operating efficiency of the system. Multiple protection levels and automatic actions are provided so that the unit is not unnecessarily tripped from the line.

The mechanical package contains the station air system, the lube oil system and most of the fuel system components. The station air system consists of a motor-driven compressor and reservoir to supply high pressure air for instruments and controls during starting, shutdown and standby periods. The lube oil system, which supplies clean, filtered oil to bearings, includes the ac motor-driven oil pump, a dc motor-driven emergency pump, an oil reservoir and an oil cooler mounted on the package enclosure roof. The oil fuel system includes the motor-driven fuel pump, fuel filters, an overspeed trip valve, a pressure regulating valve, a fuel isolation valve, and a throttle valve. A flow distributor, which serves to distribute liquid fuel equally to the 14 combustors, is located close to the turbine.

Most installations require enclosures to protect the combustion turbine against the elements, as shown in Figure 9. The enclosures are spacious, with adequate room to walk around the equipment for routine inspection and maintenance. Interior panels are perforated with acoustic treatment to control noise emission. Access to the enclosures is gained through industrial doors and, where needed, thermostatically controlled space heaters maintain the equipment at a suitable temperature level. In desert climates enclosures are often not required, as shown in Figure 10.

Figure 10. Desert ECONOPAC installation

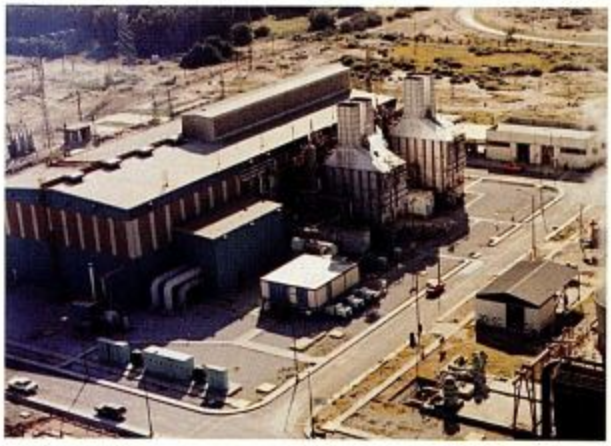


Figure 11. PACE combined cycle installation

Application flexibility

The W501D combustion turbine system has been designed to provide maximum flexibility relative to the needs of users and their architect/engineers. The system can be integrated into a wide range of locations with varying site parameters. Simple cycle units are designed to operate without the need for water unless needed for NO_X control. For sea coasts and desert-type environments, various methods of compressor inlet air treatment, including evaporative cooling and filtration, are readily available. The fuel flexible W501D, as highlighted earlier, may be furnished to operate on a wide variety of fuels: liquids ranging from naphthas to crude and residual oil and gases from solid-derived low Btu gas to natural gas.

The Westinghouse W501 axial flow exhaust system is ideally suited for heat recovery applications. The first W501 heat recovery plant went into service in 1968 and has accumulated over 79 000 hours of operation. Heat recovery for cogeneration or combined cycle/repowering applications offers a high level of efficiency. Tomorrow's integrated coal gas, combined cycle plants will provide utility and industrial customers with very attractive generation planning alternatives.

The Westinghouse PACE combined cycle plant consists of from one to five combustion turbines, each having a heat recovery steam generator, and one or two steam turbines along with associated controls and auxiliaries. Power outputs range from 135 000 kW to 675 000 kW with the potential for efficiency to approach 50 per cent. All equipment is designed for fast start-up and cyclic load swings. A typical installation of two plants, each consisting of two combustion turbine systems, two steam generators and one steam turbine generator, is shown in Figure 11.

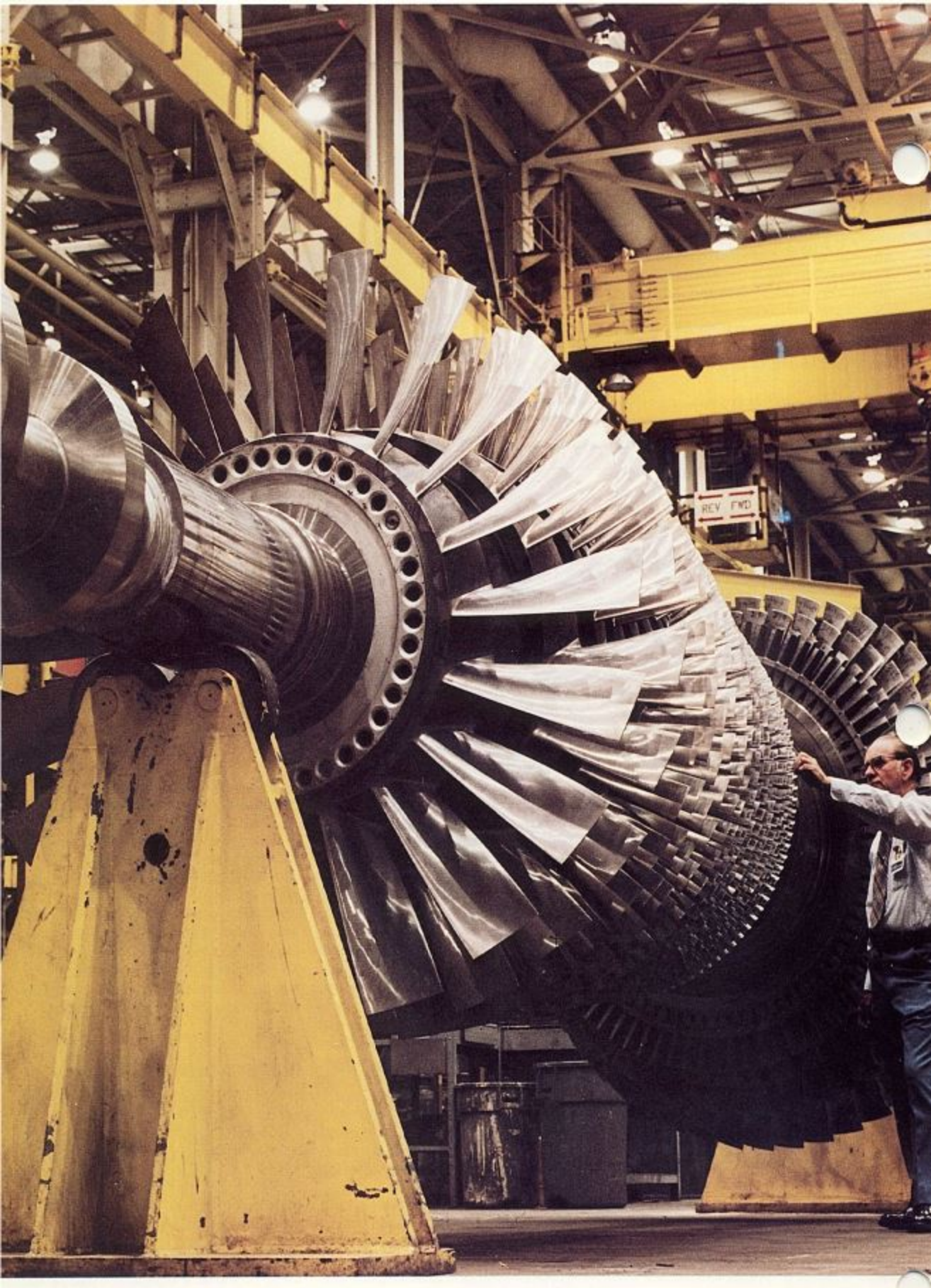
An approach that has been found attractive is to initially install a plant for simple cycle operation with planned conversion to combined cycle operation at a later date. The W501D ECONOPAC can be installed quickly to generate power during the construction of the remainder of the plant.

Of particular interest to plant designers is the Westinghouse arrangement of axial flow exhaust and generator drive from the compressor end. Besides allowing a solid coupling of turbine and generator, the fundamental plant design concept of isolating power electrics, control cabling and steam/condensate portions of the plant is more readily achieved.

Environmental impact

The W501D combustion turbine meets current US Environmental Protection Agency rules on emissions. Acceptable levels of NO_X are achieved by injecting water or steam. Smoke is reduced to an acceptable level by combustor design. The weight of particulates per unit volume of exhaust is very low in Westinghouse turbines. The W501D combustion turbine is also designed to meet existing regulations on noise. A range of standard designs is available for application depending on requirements.

Westinghouse can provide services to customers for the chemical analysis of fuel, ambient air and water, the measurement of exhaust stack emissions and the demonstration of compliance with emission and noise regulations.



Westinghouse Electric Corporation
The Quadrangle
4400 Alafaya Trail
Orlando, FL 32826-2399

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