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Cover photo: Westinghouse 501 Combustion Turbine Manufacturing Facility in Pensacola, Florida

Steam-cooled 501G rated 230 MW with 2600°F rotor inlet temperature

By Robert Farmer

First unit to ship in 1996 will be the 60-Hz model 501G rated 230 MW ISO base load—with net plant 38.5% simple cycle and 58% combined cycle efficiency ratings.

Westinghouse and its alliance partners Mitsubishi Heavy Industries (MHI) and FiatAvio are the first to announce their new 'G' series high temperature gas turbines that will operate at 2600°F turbine rotor inlet temperatures (TRIT).

The announcement, beating both GE and Siemens who are also reportedly working on their own 'G' version machines, was simultaneously made at the June ASME Gas Turbine Conference in the Hague and at Edison Electric Institute Seattle, Wash. meeting where preliminary details were released.

The alliance heavy frame machines, developed under its long-range advanced turbine project code-named Phoenix, will debut with the 60-Hz model 501G rated initially at 230,000 kW for 1996 power projects. Meanwhile, more details on the initial 'G' design and performance (and on future machines) were made available last month.

This design shows unprecedented net efficiency ratings—38.5% in simple cycle and 58% for an unfired combined cycle. It's stressed that these are net plant ratings—not gross—on natural gas fuel with typical pressure drops and auxiliaries' losses at ISO conditions 15°C/59°F ambient, sea level.

Right now, the production schedule calls for the 501G to be the first of the series, with the lead units to ship in the second half of 1996. Both Westinghouse and MHI will have 501Gs available at the same time. Expected performance for the initial machines:

☐ **Simple Cycle.** Single shaft heavy frame 3600-rpm gas turbine introductory-rated 230 MWe simple cycle with design 8,860 Btu/kWh (9,346 kJ/kWh) base load net heat rate. That's LHV on natural gas—equivalent to 38.5% packaged plant thermal efficiency. Room enough in the design envelope to grow to 300 MWe.

☐ **Combined Cycle.** Single shaft CCGT with one gas turbine, triple pressure unfired HRSG and nominal 120-MW condensing steam turbine driving one generator producing 345 MWe net plant output with a design 5,883 Btu/kWh (6,205 kJ/kWh) heat rate LHV on natural gas. Equivalent to 58.0% net plant thermal efficiency.

Alliance sources indicate that Mitsubishi already booked an order for the first 501G from a 'confidential' customer. Presumably this is from a 60-Hz electric utility in Japan, but MHI has neither confirmed nor denied this. At the same time, Westinghouse is reportedly in active negotiations with at least three potential customers in the U.S. and elsewhere, in 60-Hz application areas.

Production of 'G' class machines will take place at both Westinghouse and MHI, with the model 501G being built at MHI Takasago works and at Westinghouse Electric's facilities in the U.S. and Canada.

Both companies will also manufacture and market the follow-on 50-Hz 701G model. While Westinghouse is not saying, this machine should be rated in the 300+ MWe simple cycle class, assuming the same roughly 40% rating increase of the 501G over the 501F. (The current 701F is 234 MWe.)

It's expected that FiatAvio will produce the 50-Hz machine only, building and marketing it for primarily European applications.

According to Nick Bartol, General Manager of Westinghouse Electric's Power Generation Technology Division, Orlando, Fla., the 501G is not just one model, but a long-range Westinghouse-alliance program "to extrapolate technologies out of a basic design approach for a series of high-efficiency machines. The emphasis here is on long range, planned technology advancement that will push the performance levels of the simple cycle and combined cycle 'G' series," he says.

Leapfrog the technology

Bartol stresses that while one or another of the alliance partners (and Rolls-Royce) may be responsible for certain aspects of the G project, "we're all in this together. This is a prime example of concurrent engineering being used to bring a design to market in much less time than the more traditional methods." Here, designers, manufacturers, and suppliers all work together from the project's inception.

The G program is based on co-manufacturing and co-engineering among the three alliance partners. "There's a multi-path 'cross-talk' engineering that develops among the partners. In a sense, it almost becomes a competition as to who has the best design, or the best engineering, for each particular segment," he notes.

On the other hand, he emphasizes that a very conservative design approach was used on the G development. "G technology is an evolution of the 501D5 and 501F designs, but with performance that is revolutionary rather than evolutionary," says Bartol. The basic construction/design features are carried over from traditional Westinghouse turbine design parameters.

New machine

The 501G, however, is an all-new engine, not an uprated version of the current 163-MW 501F. It shares no components with the current 501F unit. Physically, it looks very similar to the F, but a couple of feet longer and wider—but still railway shippable. The G rotor measures 307 inches flange-to-flange, versus the 294-inch F-model rotor. A more telling comparison as to power output is overall rotor weight: nearly 59 tons for the 501G versus 46 tons for the 501F.

Internally, the two machines are also different. For example, the G features a compressor operating at a high 19.2:1 pressure ratio as compared to the F's 15.0:1 pressure ratio. Most other competitive large frame designs also operate in the 14:1 or 15:1 pressure ratio range.

According to Gerry McQuiggan, Manager, Combustion Turbine Development Engineering at Westinghouse Orlando, the G's 17-stage compressor was developed with the design basis scaled from MHI's MF221 engine compressor. (The new MF221 is rated 30 MWe, 10,665 Btu/kWh, 32% efficiency simple cycle, with a 16.0:1 compressor pressure ratio and 218 lb/sec air flow. The compressor runs at 7200 rpm.)

"The G compressor uses custom designed advanced profile airfoils," he notes, "and operates transonically in the first stage." MHI is heading up the compressor work with design and engineering assistance from FiatAvio and Westinghouse. "Like the 501F, we've gone to a bolted compressor rotor construction. We're also applying coatings to reduce compressor clearances and improve efficiency," he explains.

Steam cooling

The 501G and future G models will use steam to cool the combustor transition duct, rather than the more conventional air cooling. The main advantage of steam cooling is to reduce the amount of air taken from the compressor and applied for combustor cooling.

As McQuiggan explains it, "This allows more air to enter the head end of the combustor and so reduce the flame temperature to the same level as the 501F." Compared to the 501F, for example, the G saves between 10 and 20% of the compressor cooling air that would normally be used for combustor and transition cooling.

The advantage to steam cooling is

'F' vs. 'G' Design and Performance

These are net packaged plant ratings, with outputs at the generator terminals burning natural gas fuel at base load 59°F (15°C) compressor inlet temperature. Ratings include typical simple cycle installation pressure drops with 2.5-inch inlet and 4.5-inch exhaust duct losses, and plant auxiliaries losses.

	501F	501G
ISO Base load output	163.4 MW	230.0 MW
LHV heat rate	9470 Btu kWh	8860 Btu kWh
	9989 kJ kWh	9346 kJ kWh
Thermal efficiency	36.0%	38.5%
Pressure ratio	15.0:1	19.2:1
Air mass flow	991 lb/sec	1200 lb/sec
	449 kg/sec	544 kg/sec
Turbine inlet temperature	2350°F	2600°F
	1288°C	1427°C
Exhaust temperature	1076°F	1100°F
	580°C	593°C
Turbine speed	3600 rpm	3600 rpm

Emissions target levels for 501G

Dual-fuel low emissions combustion system operates without steam of water injection when burning natural gas. On distillate oil or other liquids, water injection is applied to limit NOx, CO and unburned hydrocarbons.

	Natural Gas (Dry)	Distillate Oil (Wet)
NOx	<25 ppm	<42 ppm
CO	<10 ppm	<25 ppm
UHC	<10 ppm	<15 ppm

Westinghouse management team. From left to right: Les Southall, Nick Bartol, Andy Ayoob and Gerry McQuiggan.

that the combustion gases are not cooled by dilution air as in conventional combustors. As he notes: "Both the F and G models operate with similar combustion flame temperatures around 1500°C to 1600°C (2732°F-2912°F). But by the time the combustion gases on the F reach the first stage turbine vane, they've been cooled and diluted down to 1350°C (2462°F). Not so on the 501G. The gas temperature ahead of the first vane remains at 1500°C (2732°F) due to steam cooling."

It also means that NOx levels will be the same as today's F models, even though the G operates at higher turbine inlet temperatures, because the combustion temperatures and residence times are nearly identical.

"The G will need around 40,000 pounds per hour of low pressure transition cooling steam at its base load output of 230,000 kW. For combined cycle plants, this steam will be taken off of the plant's existing HRSG. For simple cycle installations, a small HRSG will be fitted in the exhaust (or a separate package boiler installed) as a part of the 501G Econopac plant," he points out.

When operated at part load levels, there's a bypass valve installed in the combustor area to control the amount of combustion air bypassing the combustor flame. This is installed to provide good part load flame stability and is the same arrangement used on the 501F low NOx combustor.

Cooling design

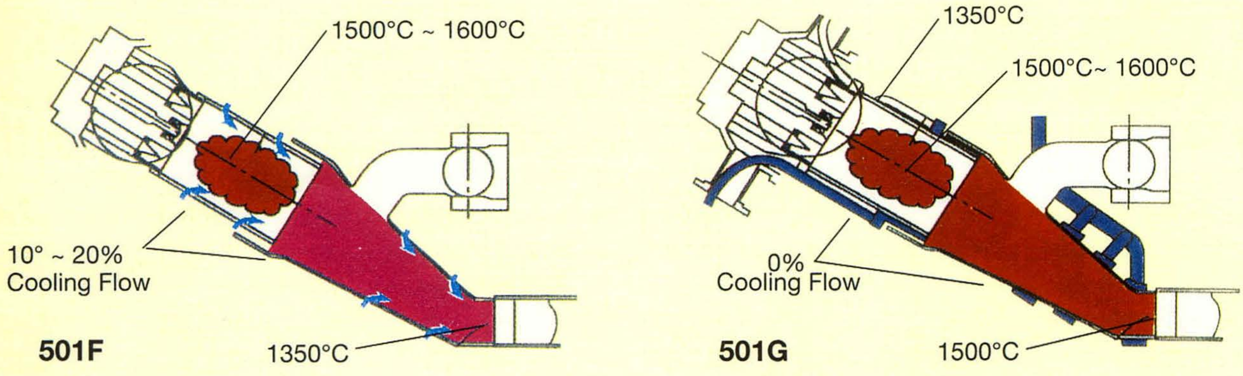
Combustor and transition cooling on both the 501G and 501F is by the MTFIN cooling system developed by Westinghouse and MHI. Basically this is a double-wall cooling design, with fins in a sandwich arrangement between the two inner walls to direct and control the cooling air (or steam, in the case of the G model).

This approach was extensively tested at the Takasago Machinery Works for the F model where test results verified that the transition cooling method makes more effective use of cooling air and optimizes the combustor outlet flow path temperature profile.

The same MTFIN design and construction is applied for the G steam-cooled unit, but it does not have the external and internal dilution holes as

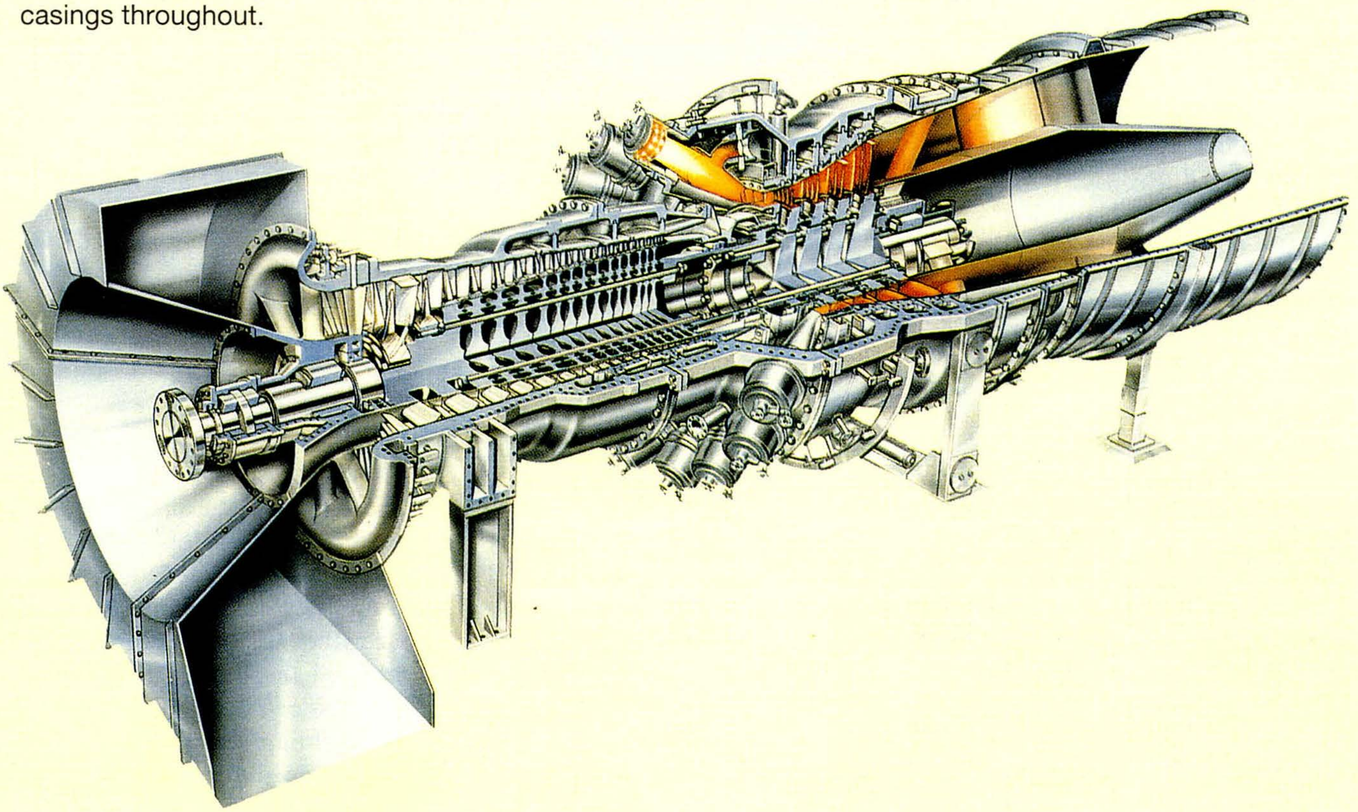
Steam conserves cooling air

Compared to the conventional 501F combustor (on the left) the steam-cooled 501G (on the right) saves between 10-20% of cooling air flow that would normally be used for combustor and transition cooling, although both operate at 1500-1600°C combustion temperatures. Steam flow on the 'G' is 40,000 pph—only around 1% of compressor air flow.



501G Design Features

Single shaft rotor is built up of compressor and turbine sections with 17-stage axial-flow compressor at 19.2 to 1 design pressure ratio. Sixteen reverse-flow, can-annular dry low NOx combustors operate on natural gas or liquid fuels, with the transition steam cooled. Four-stage axial reaction turbine applies 3-D blading design, DS materials; first three stages are air cooled. Machine includes traditional Westinghouse frame gas turbine design elements: two bearing rotor support; cold-end drive with axial exhaust; tangential exhaust bearing strut support; field-removable airfoils with the rotor in position; and horizontally-split casings throughout.



on the air-cooled combustors.

Initial 501G engines will be offered with a dual-fuel dry low emissions combustion system that's reported to limit NOx levels to under 25 ppm when burning natural gas. On distillate oil or other liquids, water injection is applied to limit NOx levels to under 42 ppm.

Operation of the 16 combustors will be closely monitored, say design engineers. There are heat sensors for each combustor that will set off an alarm if the differential temperature between combustors goes beyond the accepted level. If one combustor goes down, the entire gas turbine will shut down to avoid downstream temperature irregularities into the turbine.

Aero technology turbine

Westinghouse is heading up the turbine section design, with major technology inputs from Rolls-Royce aero engineering. The turbine is a four-stage reaction type unit and employs 3-dimensional blading design throughout the rotating blades and stationary vanes. "If you look at the airfoil profiles you'll see that they feature distinctly curved leading and trailing edges and other shape variations compared to a 2-D design," Bartol says.

He stresses that the four-stage turbine section is an important design feature. "This is typical Westinghouse turbine design, like the 501D5 and 501F. Four stages gets you the extra performance that three stage units cannot get," he claims. The four stage turbine feature may be standard on all the future G models. This design feature, plus design of the discs, shafts, bearings, etc., makes the machine capable of growth to around 300 MW.

The 501G turbine section is built with some 15% fewer airfoils than on the 501F, primarily in stages one and two. Thus, each airfoil has higher loading. This, plus sophisticated aero blade internal cooling design results in significantly less cooling air required in the turbine section.

The airfoil designs rely heavily on computer-aided design tools—3-dimensional codes—applied to industrial machines. One, for example, is the 3-D viscous flow code developed originally by Rolls-Royce for its commercial and military turbofan aero engine designs. Extensive work with these codes has, for example, allowed cutting secondary flow losses at the turbine blade-hub interface significantly.

According to Bartol, "Codes are a

Two Alliances Have Technical, Business Impact

Westinghouse Power Generation is currently involved in two, separate, long-term business and technology agreements with corporations outside the U.S. that have had—and will continue to have— a direct bearing on development of the next generation 'G' technology gas turbines, and on future designs:

The Tri-Lateral Alliance

Westinghouse Electric, FiatAvio of Italy and Mitsubishi Heavy Industries of Japan formally agreed to cooperate in development, manufacture and marketing of gas turbine technology under a 10-year agreement that became effective in May, 1991. This alliance effectively makes MHI and FiatAvio business corporate partners with Westinghouse.

The three have been cooperating on gas turbine design and development for decades under other arrangements—Fiat since 1954 and MHI since 1961. Both also hold product licenses for production and sale of Westinghouse-designed gas turbines.

The trilateral pact is aimed at enhancing the three companies' positions in the world power generation business. It provides for shared technologies, flexible manufacturing arrangements and cooperative sources of turbine components and materials. It also covers joint programs to source low-cost materials and components for existing and new gas turbines

More importantly, it specifically aims to cooperatively develop, market and supply gas turbines and combined cycle power plants. This covers the existing frame machines built by the three, and development of advanced technology units, such as the current 2300°F firing temperature 'F' technology for the 501F and 701F—and now the 2600°F 'G' series.

Separately Westinghouse and MHI have a similar cooperative technology arrangement for steam turbines and a 10-year technical exchange and cooperative development program for electrical generators for all types of power plants.

Westinghouse-Rolls-Royce tech exchange

Separately from the tri-lateral pact above, an engineering and marketing alliance was signed in 1992 between Westinghouse and Rolls-Royce. This 15-year cooperative agreement calls for development and marketing of land-based gas turbines and combined cycle power plants as a two-way technical exchange.

Rolls-Royce is transferring aircraft engine technology to Westinghouse that is being incorporated in the current range of heavy frame turbines—and new designs such as the 'G' series—produced by the tri-laterals Westinghouse, MHI and Fiat.

For its part, Westinghouse is transferring selected steam turbine, steam cycle, gas turbine and combined cycle technologies to Rolls-Royce. The two are also cooperating on R&D programs that extend the Westinghouse 60 Hz combined cycle package designs to 50 Hz.

To date, the R-R alliance products include the 50-MW Trent genset package and the 27-MW RB211 EconoPac. And, while not covered under this accord, the WR-21 intercooled recuperative marine gas turbine being developed jointly with Westinghouse Marine.

way of designing a new machine and its component parts with reduced individual component testing. We're certainly not giving up on testing," he emphasizes, "but codes speed up the design work tremendously and help to focus verification testing on the critical areas."

Last stage turbine rotor blades are up 25% in size over the 501D5/F models to handle the increased mass flow and power. Stage four blades are large—with about 25-inch blade length. That's up there in steam turbine territory. Integral 'Z' tip shrouds are employed on the 3rd and 4th stage blades (same as the 501F/701F) to minimize the potential flow-induced non-synchronous vibration. The G will also have shroud cooling on row 3 turbine blades.

Air-cooled turbine

The first three turbine stages are air-cooled—all rotor blades and stationary vanes. (The fourth stage is uncooled.) Compressor discharge air bled from the combustor shell is first directed through an external air-to-fuel cooler/filter assembly, and then to the turbine section.

Air cooling is sophisticated aero technology and the stage one and two rotor airfoils will be protected by thermal barrier coatings as well. Much emphasis will be on the thermal barrier coatings in the front turbine stages to handle the higher temperatures.

Maximum metal temperatures will be the same as today's F-technology engines. Considerable attention was also paid to reducing the amount of cooling air required by the turbine section and to minimize leakage air in the seal systems.

"Design parameters at ISO base load are 2732°F (1500°C) gas temperature at the leading edge of the first stage nozzle segments," McQuiggan reports. "We'll see 2600°F (1427°C) turbine rotor inlet gas temperature, measured after the first nozzle, just ahead of the first rotating blade." By way of comparison current high-performance military aircraft engines are running around 2850°F turbine inlet temps on full power.

Nevertheless, the G is still a hot engine by industrial standards. In addition to advanced airfoil cooling design and thermal barrier coatings, the alliance has gone to directionally-solidified cast blades and vanes for the first and second stages to handle the higher temperatures and provide long life.

The bill of materials for blades, vanes and coatings has not been released. However, work by MHI in conjunction with Tohoku Electric in Japan might provide a clue as to what is being used. A joint development program run at MHI's Takasago Works features a high temperature demonstration unit (HTDU) aimed at 1500°C (2732°F) "firing temperature", which is in fact combustor exit temperature.

Advanced heat-resistant materials and designs are a major part of the HTDU effort. Row one airfoils made of currently-applied conventionally-cast ECY768 and IN738LC in various cooling designs are being tested against advanced aero-type nickel alloys.

These advanced blades and vanes include both directionally-solidified and conventionally-cast Mar-M247 and IN939M. Various compositions and thicknesses of thermal barrier coatings are also being tested.

With advanced blade cooling designs, skin and average metal temperatures of the G airfoils throughout the four stage turbine section are reported to be in the 501F range even at the G's higher gas temperatures. The 501F's first stage vane at 2300°F TRIT shows an average metal temperature of 1400°F and a maximum surface temperature of 1600°F, according to Westinghouse reports.

Blading sourced from R-R

The first and second stage directionally solidified turbine rotor blades are sourced from Rolls-Royce, out of a new production facility in England. Earlier this year, Westinghouse awarded Rolls-Royce a £14 million ($22 m) four-year production contract for directionally solidified turbine blades for the 501G.

The DS airfoil project reportedly could be worth up to £60 m ($93 m) out through the year 2005 for the 501G and other G variants, R-R reports.

The airfoil designs are said to be similar to the aero Trent 800 high pressure turbine airfoils, but much, much larger. First stage vane cooling is accomplished by a combination of impingement, film and convective cooling. Impingement inserts inside the vane work with showerhead, film cooling, and pin fin trailing edge cooling.

The first stage blade applies film and convection cooling techniques, using multipass turbulated serpentine passages with external pressure and suction side film cooling. Advanced aircraft engine designs including shaped film cooling holes and angled turbulators are applied as well.

Rolls-Royce Turbine Aerofoil Manufacturing operation in Derby will produce the precision cast blades, supplying them as machined, fully finished and coated to Westinghouse production facilities in North America.

Mechanical design features

As noted, the single-shaft 501G design draws heavily on traditional Westinghouse heavy-frame gas turbine design elements. These include: two bearing rotor support with no center bearings in the hot section; cold-end drive with an axial exhaust duct; tangential exhaust bearing strut support; field-removable airfoils with the rotor in position; and horizontally-split casings throughout to provide access to internal parts.

—Rotor. The single shaft rotor is built up of separate compressor and turbine sections joined by a center coupling. Compressor and turbine rotors are constructed of through-bolted discs. Turbine discs are interlocked through Curvic couplings. The completed rotor rides on two 18-inch tilting pad journal bearings, with thrust handled by a 25-inch tilting-shoe bearing.

—Compressor. A 17-stage axial-flow compressor has a design pressure ratio of 19.2 to 1 with a base load air flow of 1,200 pounds per second. One row of variable inlet guide vanes serves to maintain part load performance, reduce starting equipment demands, and regulates exhaust temperature in heat recovery applications. Two exit guide vanes straighten the flow coming out of the compressor.

The design features compressor blade rings, individually removable stainless steel blading, double-acting thrust bearing and cold end drive with a solid coupling to the generator. Compressor diaphragms are coated to protect against fouling.

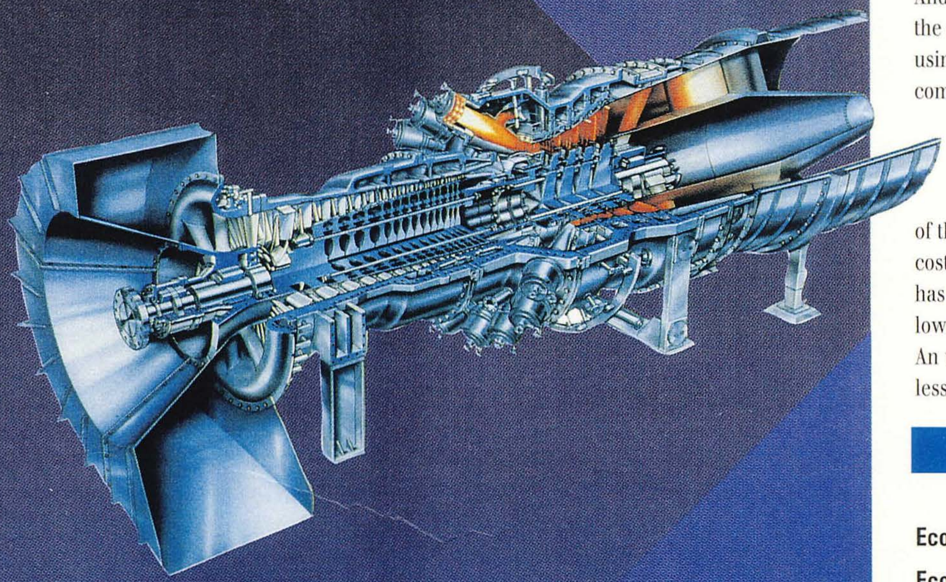
—Combustor. Sixteen reverse-flow, can-annular dry low NOx combustors are fitted for operation on gaseous or liquid fuels. The transition is steam cooled. Two igniters, each installed in a separate combustor together with cross-flame tubes provide ignition. A thermocouple array downstream of the turbine is used to monitor combustion functions.

—Turbine. The four-stage axial reaction turbine applies 3-D blading design, and the first three stages are cooled with compressor bleed air. The first and second stationary vane and rotating blade stages are directionally solidified castings, with advanced cooling designs. First two stages of blades and vanes are protected with thermal barrier coatings.

—Bearings. The journal bearings are two-element tilting pad types for load carrying with an upper-half fixed bearing to eliminate top pad flutter and possible local babbit spragging. Leading edge groove (LEG) direct lubrication is specified to reduce lube oil flow and associated mechanical losses.

—Exhaust. Turbine exhaust cylinder houses the aft journal bearing and is supported by eight tangential struts that maintain alignment. Extended axial-flow diffuser cuts pressure losses, lowers exhaust gas velocity before it enters the stack or the heat recovery boiler. ■

The World's Largest And Most Efficient 60 Hz Industrial Gas Turbine



501G

THE ECONOMIC CHOICE

The Westinghouse 501G is the world's largest and most efficient 60 Hz industrial gas turbine. The 230 MW "G" will produce the highest combined cycle efficiencies in the industry. For baseload, intermediate, or peaking duty, the 501G is the clear economic choice.

PROVEN DESIGN CONCEPTS

The 501G incorporates a two-bearing rotor, axial exhaust, cold-end drive, individual combustors and other field-proven features. The latest aero design codes, materials, and design concepts including directionally solidified blading and thermal barrier coatings are used. And, the 501G can be adapted to meet the emissions requirements of your site using the latest in dual fuel dry low NO_X combustion systems.

LOWER LIFE CYCLE COSTS

Minimizing life cycle costs was an important objective in the design of the 501G. Complementing its low capital cost and low fuel consumption, the 501G has 15% fewer hot parts — contributing to lower maintenance costs. The end result: An unprecedented low cost of electricity — less than 90% of current technology values.

501G PERFORMANCE

Natural Gas, ISO, Net

EconoPac Output, MW	230
EconoPac Heat Rate, Btu/kWh (kJ/kWh) LHV	8,860 (9,347)
EconoPac Efficiency	38.5%
Exhaust Temperature, ^{0}F (^{0}C)	1,100 (593)
Exhaust Flow, lb/sec (kg/sec)	1,200 (545)

Raising Combustion Turbine Technology To The Next Power

Westinghouse Electric Corporation
Power Generation Business Unit
4400 Alafaya Trail
Orlando, Florida 32826
(407) 281-2000