

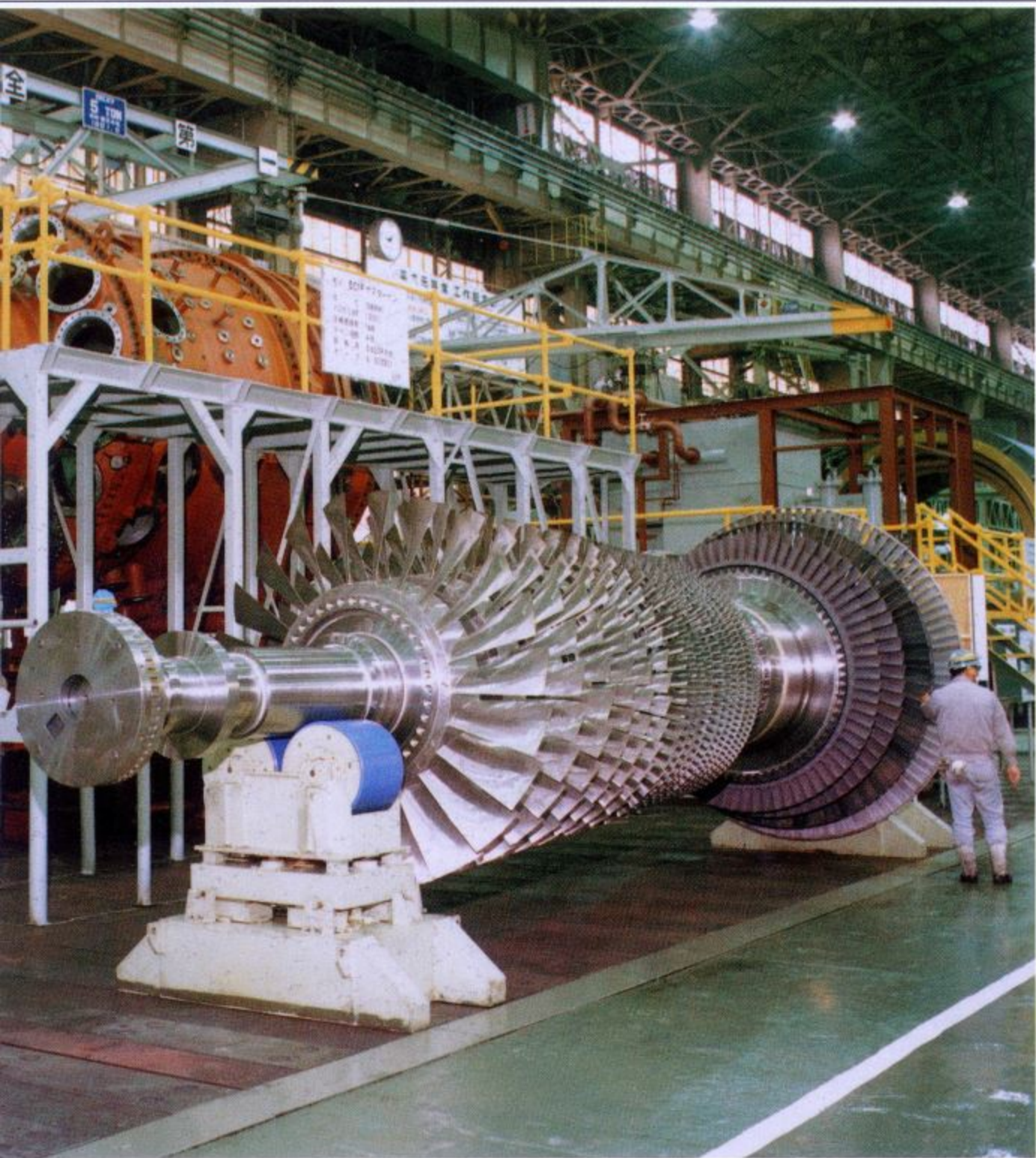
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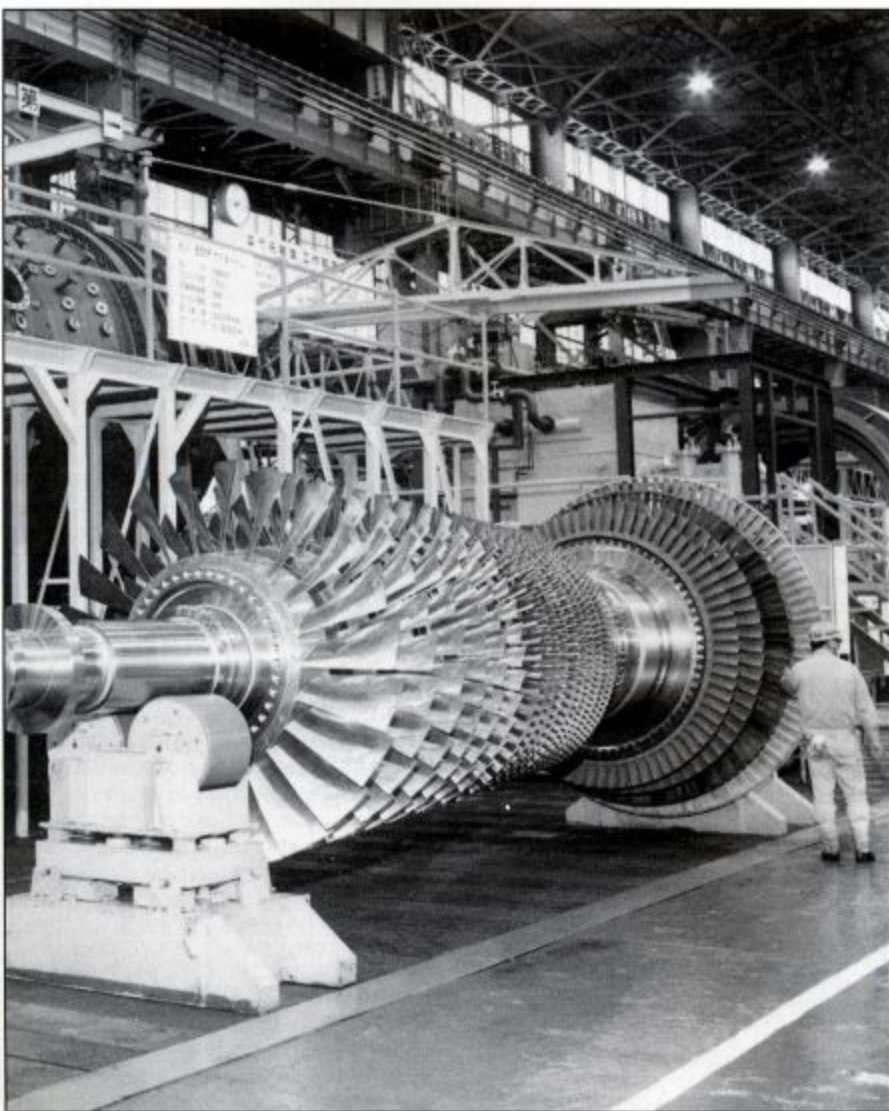
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150 MW Class 501F design to begin full load factory testing this summer

By Robert Farmer

Packaged plant, design rated at 148,800 kW ISO base and 34.8% efficiency on gas fuel, is expected to sell for under \$200 per kW installed — is scheduled for field service evaluation in 1990.



Rotor assembly for the 150-MW class 501F gas turbine developed jointly by Westinghouse and Mitsubishi.

By mid-July this year, the first 150-MW class 501F gas turbine — developed by Mitsubishi Heavy Industries and Westinghouse Combustion Turbine Operations — is scheduled to begin full-load, full-temperature factory tests at MHI's Takasago Works.

Both team members are sharing design, engineering, development and project financing to bring the advanced technology, high temperature (2300°F) machine to the electric utility and industrial power marketplace for 60-Hz projects worldwide.

Right now, both Westinghouse and MHI are actively quoting the machine to candidate "host site" customers where the prototype will be installed following the successful completion of factory testing later this summer. Here, the machine will be installed as either a simple or combined cycle set (the latter possibly repowering an existing steam turbine) for field test operation in 1990.

Initially, the prototype installation will be operated at the introductory rating of 138,500 kW (gas fuel) at a turbine inlet temperature of 2210°F (1210°C). As running hours are chalked up, the temperature will gradually be increased to the full 2300°F (1260°C) rating point, with the subsequent increase in output to 148,800 kW.

Meanwhile, production shipments of introductory-rated engines could begin as early as 18 to 20 months after the completion of the factory test program — meaning possible availability by 1991. Fully-rated units are now scheduled for shipment by the middle of 1992. Both versions are designed for a variety of power applications, including:

Simple Cycle Power Generation. For peak shaving to mid-range operation around 3000 hours per year, packaged 501F generator sets will feature a mature ISO base load output of 148,800 kW at the generator terminals, with a 9800 Btu/kwh base load heat rate — equivalent to 34.8% simple cycle efficiency. That's on natural gas fuel. Liquid fuel ratings are 143,600 kW ISO base with a 9925 Btu/kwh heat rate. Packaged plants expected to sell for under \$200/kW installed.

Combined Cycle Base Load. Optimized combined plant, built around a

single 501F, unfired three-pressure level HRSG, and double-case 65-MW steam turbogenerator will be rated 210,000 kW ISO base load output — with an outstanding 6800 Btu per kWh heat rate — equivalent to 50.2% LHV thermal efficiency. Ratings on natural gas fuel with 1-inch HgA condenser pressure. Anticipated price for an installed single-unit combined cycle plant is around \$500 per kW.

□ **IGCC Coal-Fired Plant.** In case of future gas/liquid fuel price escalations or supply restraints, 501F combined cycle is designed for easy conversion to integrated gasification plant operating on medium-Btu coal-derived gas. Projected plant output for converted single-501F combined cycle would be 245,000 kW ISO base load output and 6800 Btu/kwh net plant heat rate on 300-Btu coal gas fuel.

The 501F joint effort project was initiated in 1985, following extensive discussions between Westinghouse CTO and Mitsubishi, who have been building Westinghouse-designed industrial gas turbines under license since the early 1960s. In addition to the Westinghouse machines, MHI produces its own MW-701 (scaled from the W-501 for 50-Hz service), the MW-252 (a twin-shaft variation of the W-251 frame) as well as its original design units in the high-temperature MF-111 series.

Basically, the 501F project charter called for pulling advanced component and design technology from a variety of different sources available to the two companies — and melding it into an industrial machine based on field-proven design practices.

As such, the basic layout of the machine is quite similar to what might be called the Westinghouse design philosophy found in their gas turbines that in some cases have been around for nearly 40 years. Some of these proven design elements include: two-bearing rotor support; cold-end drive with an axial exhaust; tangential exhaust bearing strut support; horizontally-split casings; and field-removable airfoils without rotor removal.

The advanced technology features came from a host of different sources. As Augie Scalzo, Westinghouse CTO's technical director explains, "To overly simplify, you can trace the 501F genealogy to our current W501D5 design concepts, MHI's low-NOx combustor technology from the MW701D and its high-temperature air-cooled blade and vane technology from the MF-111.

"All of the new technology components, especially the air-cooled turbine and the combustors have gone through extensive performance and design verification testing at MHI's facility," notes Scalzo. "The Takasago Works test program, recently successfully concluded,

501F Base Load Performance

Nominal performance figures for a gas-fired simple cycle generator set at the introductory firing temperature — and the mature 2300°F temperature. Output on liquid fuel is slightly lower (x .965) while heat rate is higher (x 1.013) than on gas.

Performance Parameter	Introductory	Mature
ISO Base Net Output.....	138,530 kW	148,800 kW
Heat Rate Btu (LHV)	9910 Btu/kWh	9800 Btu/kWh
Heat Rate kJ.....	10,455 kJ/kWh	10,340 kJ/kWh
Thermal Efficiency	34.4%	34.8%
Pressure Ratio.....	14:1	14:1
Air Flow Lbs	914 lbs/sec	914 lbs/sec
Air Flow kg.....	414 kg/sec	414 kg/sec
Turbine Inlet Temperature.....	2210°F	2300°F
Turbine Inlet Temperature.....	1210°C	1260°C
Exhaust Temperature	1004°F	1053°F
Exhaust Temperature	540°C	567°C

Note: ISO standard conditions, gaseous fuel, net ratings at the generator terminals, without inlet or exhaust duct losses.

included rotating blade vibration tests on the first two compressor rows and all four stages of the turbine; turbine aerodynamic performance verification; and performance and pressure-testing of the improved design hybrid combustors," he explains.

The 501F prototype rotor is now being bladed at MHI's factory in preparation for the engine shop test verification program this July. Here, the heavily-instrumented gas turbine will be installed with its ac generator, with electrical output being absorbed by a water rheostat at the test facility — allowing full temperature, full load dynamic testing of the complete engine. These first shop tests are scheduled on liquid fuel, while field evaluation units(s) will operate on gaseous fuel.

"We'll be looking at results from the shop tests to confirm several areas of design and performance predictions. Specific areas include engine starting and acceleration characteristics; compressor inlet flow over the IGV range, and overall compressor surge margin performance; emissions characteristics; mechanical and thermal performance of the machine from startup through overspeed; and of course a complete 'map' of gas and metal temperatures, pressures and vibratory characteristics," Scalzo concludes.

General Design Characteristics

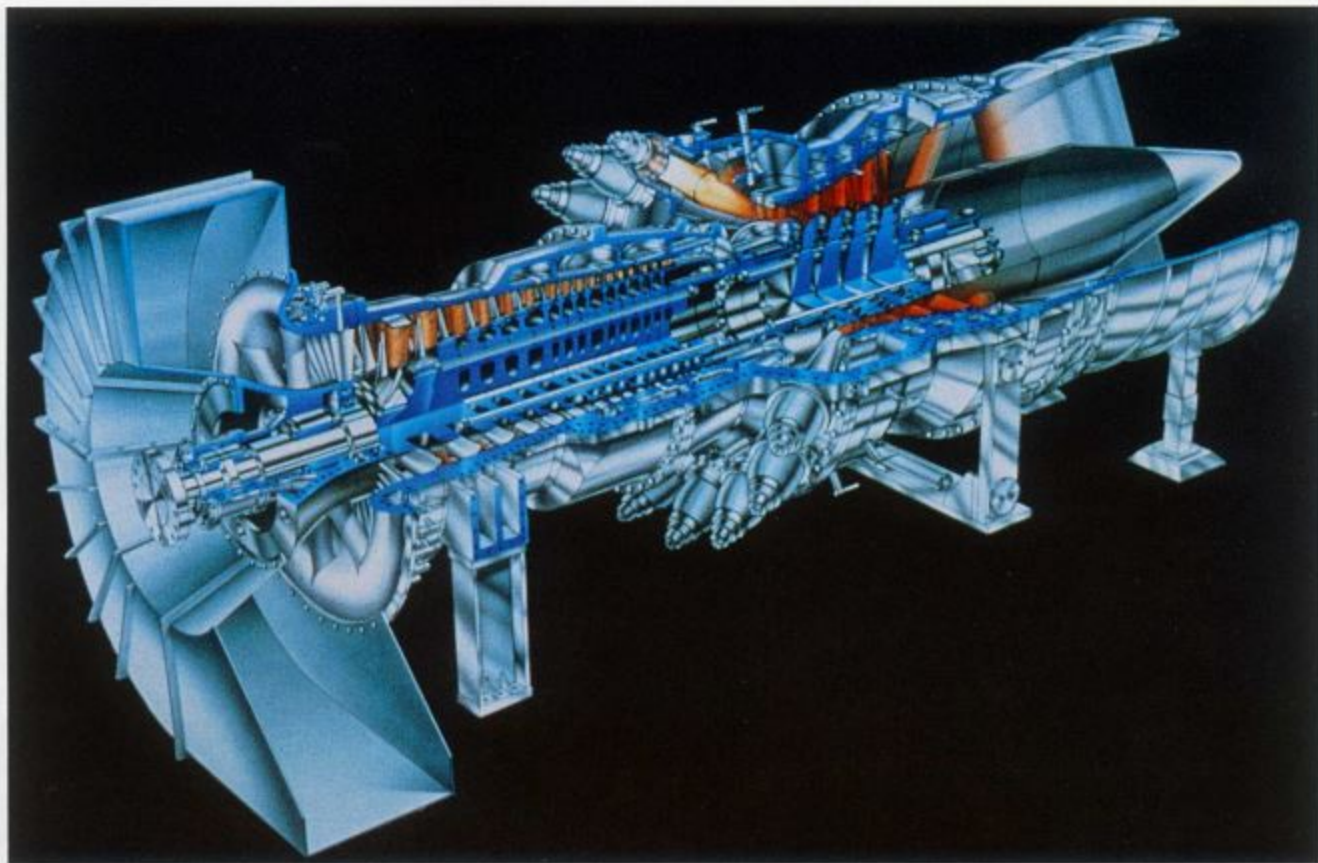
The 501F is a heavy frame, single rotor machine designed for 3600-rpm continuous duty operation for 60-Hz electrical power generation. The bare en-

gine measures slightly over 37 feet long by nearly 14 feet high by 13 feet wide, and weighs 360,600 pounds. Its design/construction features include:

Compressor. A 16-stage axial-flow compressor with a design pressure ratio of 14 to 1 and a base load airflow of 914 lb/sec features variable geometry inlet guide vanes. Built up of through-bolted discs with rotor blades and stationary vanes of AISI 403 stainless, except the first two rows which are 17-4PH stainless. Stages 7 through 16 feature blade rings supporting the stationary components. This design provides thermal response that's independent of the outer casing — allows exact concentric alignment with the rotor for minimum clearance, thus improved compressor performance.

Variable Geometry Guide Vanes. Compressor fitted with variable inlet guide vanes ahead of the first stage — with blade angle adjusted automatically by power plant controls to improve compressor low speed surge characteristics during start-up. IGV's also effective in improving part load efficiency, and — in combined cycle applications — provide faster steam cycle warm up.

Dual-Fuel Combustor. Sixteen individual annular diffusion-flame type combustors are fitted. Can operate on either gaseous or liquid fuels, or any combination of the two, and can switch between gas and liquid while machine is at full load output. Controls NOx to 25 ppm (gas fuel) and 42 ppm (liquid fuel) with steam/water injection. Com-



The 501F gas turbine is built around 16-stage axial compressor with variable geometry inlet guide vanes and dual-row exit vanes coupled with a four-stage axial turbine featuring air cooling on the first three stages. The 16 combustors are low-NO_x can-annular hybrid type. Entire rotor is supported on two journal bearings with one thrust bearing at the forward end. Overall engine measures 37 x 13 x 14 feet (lwh), weighs 360,000 pounds.

bustor basket is of Hastelloy-X with the transition duct in Tomillo.

Low-NO_x Hybrid Combustor. Sixteen hybrid type combustors are available to meet NO_x regulations of 75 ppm on gas fuel without any steam or water injection — will ultimately produce 30 ppm NO_x “dry” on gas fuel with completion of ongoing development program. With relatively low levels of water/steam injection, current designs achieve NO_x levels down to 25 ppm (gas) and 42 ppm (liquid). Combustors currently configured for gas- or distillate-only operation, with dual-fuel systems to be available in the near future. Hybrid design combines standard diffusion burner as the pilot combustor with the main burner using pre-mix technology for low NO_x.

Cooled Combustor and Transition. Hybrid combustor design also features a plate-fin type wall structure, developed by MHI and in service on their MF111 machines. Dubbed MTFIN, it is a double layer composite “sandwich” structure with cooling channels being the filling between the two slices of Hastelloy-X. Extremely effective cooling design is said to reduce the amount of combustor cooling air by 50% over con-

ventional combustors. Means more air is available for NO_x reduction services. Concept also applied to the transition pieces.

Air-Cooled Turbine. Four-stage turbine section has air-cooled vanes and blades on the first three stages to accommodate the design 2300°F inlet temperature while keeping average metal temperatures below 1470°F for long component life. Vanes on rows 1 and 2 are precision cast ECY768 while rows 3 and 4 vanes are cast in X45. The first three stages of blades are cast Inco 738 and the final stage is forged U 520 material. All stationary airfoils feature blade rings to minimize clearances, prevent blade rubs. Turbine discs of NiCrMoV have Curvic couplings for positive alignment, through-bolted with 12 tie bolts.

Tilting-Pad Bearings. Rotor support by two pressure-lubricated journal bearing — one at front, one at rear — and single front-mounted thrust bearing that features leading edge groove lubrication. Lower half of the journal bearing — the portion that carries the rotor load — is of tilting-pad construction; top half is plain to eliminate pad flutter and local babbitt failure problems.

Protective Coatings. All turbine section row 1 and 2 airfoils feature a NiCo-CrAlY plasma spray protective coating standard, or optionally, a variation of the standard coating applied by electron beam vapor deposition. The compressor diaphragms are coated with a ceramically-bonded aluminum base coat with a chromate/phosphate top coat. This same coating is optionally applied to the rotor blades for machines destined for corrosive environments.

Operation and Performance

When the first 501F models become fully operational, start-up will be initiated by a single-button on the digital Power Logic II control system that will completely control the genset from cold start to full load. It provides all the sequencing, modulating control and data acquisition tasks in one integrated package.

“With low-NO_x combustors fitted, the critical concern during starting is not so much the NO_x emission levels, but rather the flame stability,” Scalzo points out. The hybrid combustor design utilizes a two-stage burner assembly comprised of a pilot burner and a main burner, with a bypass valve



Air-cooled first stage turbine blades use combination of impingement, film and pin-fin cooling techniques to keep average metal temperatures below 1470°F at base load turbine inlet temperature of 2300°F.

that's designed to inject some of the compressor discharge air directly into the transition duct during start-up and low-load operation.

"This air injection provides a stable flame at this period when only the pilot torch is operating. This is required, in part, because the ratio of pilot burner fuel to main burner fuel has been trimmed considerably as compared to MHI's W701 hybrid combustor design.

"When the main burner starts to kick in, at about 40% of full load, the bypass valve is modulated to keep a constant fuel-to-air ratio, thus reducing NOx emissions during the critical loading phase. At full load, the bypass valve is fully closed and the combustor operation is similar to a conventional combustor," he explains.

During starting, the control system also modulates the compressor inlet guide vane geometry — to avoid low speed surge — and activates interstage bleeds at stages six and ten. These bleed locations are used to provide internal component cooling air for turbine stationary stages four and three (respectively) during normal operation. Second stage turbine vanes are cooled by air taken from the compressor stage thirteen, while compressor discharge air is used on turbine vane stage one.

Full base load operation sees design 2300°F gas temperatures at the inlet to the first stage turbine rotating blades. While Westinghouse and MHI aren't quoting figures, this would indicate somewhere around 2600°F gas temperatures at the inlet to the first stage vane. This is a hot engine.

Yet with these kind of gas temperatures, the advanced cooling designs

produce component metal temperatures nearly identical to the current W501D5 and MW701 machines that operate at turbine inlet temperatures more than 300°F lower — at some 2000°F ISO base load.

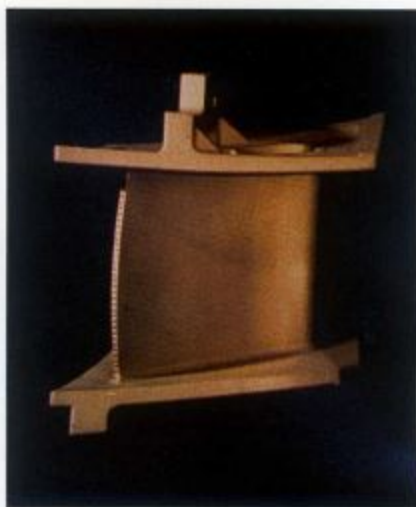
The answer is extremely sophisticated blade cooling designs. Each first stage vane segment, for example, utilizes three impingement inserts, a large number of film cooling holes and a trailing edge pin fin cooling configuration. Compressor discharge air at around 750°F at base load conditions is directed to the vane's forward two impingement cavity inserts to provide maximum air pressure, while the aft cavity insert gets spent shroud cooling air to meet its lower pressure requirements.

"We've found that this vane cooling configuration — which evolved directly from our W501D5 design — is very effective," notes Scalzo. "In particular, the pin fin system promotes increased turbulence and increases the surface area to optimize the overall trailing edge cooling effectiveness."

The row two vanes feature a similar cooling design, somewhat less complex, but still utilizing the combination impingement, film and pin fin cooling techniques. Cooling air for row two comes from the 13th stage compressor bleed.

Stage 10 compressor bleed air is used to cool the third stage vanes in a three-cavity, multi-pass convection-cooled design. Fourth stage vane is uncooled as gas temperatures at that region are only about 1200°F at base load.

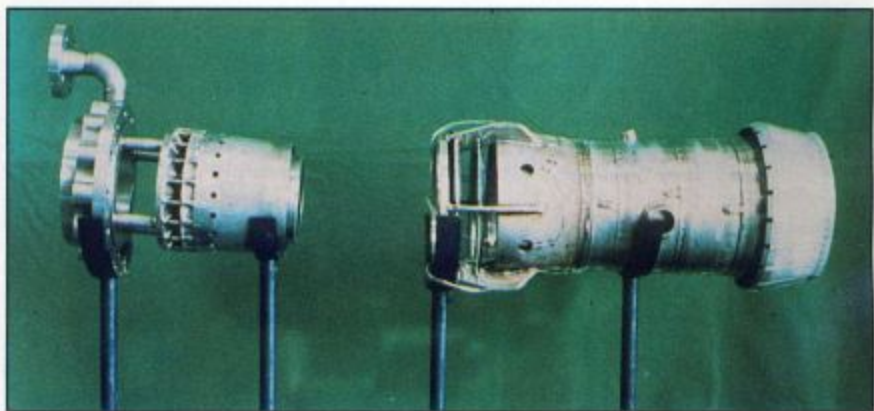
The turbine's first stage rotating blades are cooled by a combination of convection techniques with multiple-pass serpentine internal passages and pin fin cooling in the trailing edge slots. Leading edge of the blade is cooled by a combination of shower head film cooling and internal impingement cooling. Similar, though less compli-



First stage turbine vane is cast in individual segments of ECY768 material with a NiCo-CrAlY corrosion-resistant coating. All turbine section stationary airfoils feature blade ring inner casing design to minimize distortion and maintain critical vane angles.



Vanes segment for the third stage is precision-cast X45 material, cooled by compressor bleed air from the 10th stage. Third stage is made up of 16 of these three-vane segments.



Hybrid low-NOx combustor showing the premixing nozzle assembly at left, which inserts into the combustor basket, right. Basket and transition piece (not shown) feature plate-fin cooling design that cuts cooling air flow by 50% over conventional designs — provides more dilution air to cut NOx formation.

cated systems are used in the second and third stage blades. Fourth stage blades, like the fourth vanes, are uncooled.

Due to the high operating temperatures, coupled with the relatively complex rotating blade cooling passages, the 501F design uses cooled and filtered high pressure compressor discharge air to cool the first three stages of turbine blades.

"Compressor discharge, at around 750°F and 205 psig is directed off the engine to a skid-mounted inertial filter-air cooler assembly which drops its temperature to 375°F regardless of ambient conditions. The inertial type filter has an efficiency of 87% for 5-micron particles, and an efficiency of 90% for coarse dust — the type of stuff that could clog minute, intricate cooling holes and lead to blade damage," Scalzo indicates.

Cooled and filtered air is reintroduced into the engine at the torque tube casing. In addition to supplying turbine blade cooling, it also provides seal air and disc cooling services. In fact, the entire disc assembly is cooled to metal temperatures below 750°F. As company design engineers point out, that is below the alloy's creep range — meaning that disc life is limited only by corrosion and wear.

Maintenance and Inspection

Target goals for the 501F operation include 97% availability and 95% starting reliability where, by industry standards, availability is defined as "period hours less combined forced and scheduled outage hours divided by period hours"; and reliability defined as "period hours less forced outage hours divided by period hours."

To reach those goals requires not only excellent equipment and auxiliaries design and construction, but the ability to inspect and repair in the shortest possible time in order to get the plant back on line or available for duty.

Most of the routine maintenance and inspection of the gas turbine is designed to be done without the need for engine cover lift. Borescope ports are located at key locations to allow visual inspection of nearly all the compressor and turbine blading without disassembly. There are manways at the inlet and exhaust housings to provide inspection of front and rear engine components and blade paths.

Additional manways provide access to the combustor section to provide for visual inspection, removal and replacement of combustors, transition pieces, and first stage turbine single vane segments. They also provide access for center plane balancing, if required.

Normal field balancing, however, is

of the two-plane variety, with balance planes externally accessible at the inlet and exhaust ends of the rotor. Also external is all maintenance/inspection/removal operations for the combustor fuel nozzles.

Engine cover removal is required to get at the compressor and turbine blades and vanes (with the exception of row 1 turbine vanes). Horizontally-split casings provide several independently-removable engine cover sections, meaning the whole "clamshell" case does not have to be lifted to gain access, which should be effective in reducing down time.

Compressor diaphragms (stationary vanes) on the aft ten stages feature blade ring design, as do all four turbine vane stages. This allows the worker to "roll out" the stationary airfoils without disturbing the rotor. All compressor diaphragm seals are now removable without removal of the diaphragm — to allow field replacement of the seal and easy access to inspect the tenon welds. With the cover(s) removed, all rotating blading is available for individual removal or replacement without rotor removal — and without disturbing other airfoils.

Finally, both the journal bearing and the thrust bearing can be removed and replaced without rotor removal. Journal bearings at the front and the rear of the rotor are easily removed by using a special trolley assembly — without having to split and lift any major engine casings.

Possible 50-Hz Offspring

While neither MHI nor Westinghouse are saying, it seems likely that a 3000-rpm version of the 501F will be developed to offer high performance simple and combined cycle plants to the 50-Hz industrial and utility market.

A "701F" model could be scaled up from the current 501F, just as MHI scaled its 50-Hz, MW701 frame from the 60-Hz W501. Using a 1.44 scale factor to convert 60-Hz to 50-Hz, a new 701F model would feature an introductory ISO base load rating estimated at 199,500 kW — and a mature rating up around 214,500 kW with a 9800 Btu/kwh base load heat rate.

Similarly, an optimized gas-fired combined cycle plant built around a single 701F, unfired multi-pressure level boiler and double casing steam turbine generator could be rated between 305,000 and 310,000 kW ISO base load — with better than 50% LHV net plant thermal efficiency.

Tracing the Roots of the 501F

Like most family trees, the further back you go, the more complex the genealogy becomes.

For example, while the 501F's compressor design is patterned after the W501 series, in fact the first four stages of the "F" utilize an aerodynamic design that originated in good part with a joint Westinghouse-Fiat redesign of Fiat's 130-MW TG50 compressor that was carried out in 1984.

Stages five through 16 of the F compressor are based on an air-foil design derived from the 1950s-vintage NACA 65 series airfoil modified by the former Westinghouse Aviation Div. and known as the W65 airfoil.

Both the NACA and Westinghouse airfoil designs were subjected to extensive testing by the respective groups, with the W65 design featuring modified leading and trailing edge geometry.


The high-temperature turbine design comes from a varied parentage. Some of the technology was pulled from the Westinghouse W1501 program from the 1970s. This single shaft, 150-MW machine, designed but never built, featured blade and vane cooling technologies designed to handle a base load 2200°F turbine inlet temperature. The 501F first stage turbine vanes, for example, use cooling techniques developed for the W1501 and first employed and proven in the latest "D5" iteration of the W501 machine.

Some of the turbine section aerodynamic design concepts also came from MHI's participation in Japan's government-industry-utility-sponsored project "Moon Light" launched in the early 1980s to develop an advanced, high temperature industrial gas turbine.

While most of the actual blade and vane cooling technology was taken directly from the high-temperature MF111 machine (2100°F TIT), the technology can also be traced to Moon Light as well as to advanced aircraft engine blade cooling techniques utilized by MHI and others.

The "hybrid" low-NOx combustor that serves as the basis for the improved 501F combustor was developed by MHI and installed in the MW701Ds that began operation for Tohoku Electric in late 1984. These machines have demonstrated dry NOx levels to 60 ppm on natural gas fuel in commercial utility service at 1985°F turbine inlet temperatures. However, the original "hybrid" concept (premix, lean burn combustor) was developed by a Westinghouse engineering team in the mid-1970s, although not applied to an engine.

And Mitsubishi's "MTFIN" plate-fin combustor and transition cooling configuration was developed in part based on advanced aircraft combustor cooling designs, coupled with technology from Moon Light and proven in several MF111 series machines that have been in commercial operation since 1986.



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