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TITAN 130 UPDATE FOR POWER GENERATION AND MECHANICAL DRIVE APPLICATIONS

by

Martin Habel
Rainer Kurz
George Rocha
Mohammad Saadatmand

of
Solar Turbines Incorporated
Division of Caterpillar Incorporated
San Diego, California

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ABSTRACT

The *Titan* 130 industrial gas turbine was introduced into commercial service in 1998 and has gained field experience in oil and gas power generation and mechanical drive applications. It is available in a single-shaft configuration for power generation and in a two-shaft configuration when used as a mechanical drive. The *Titan* 130 single-shaft engine is nominally rated at 14.25 MWe output power and 35% efficiency at the generator terminal at ISO operating conditions. The *Titan* 130 two-shaft engine is nominally rated at 19,500 hp with more than 35% efficiency at ISO operating conditions. The engine is available with two combustor options: a dry, low-pollutant emissions combustion system featuring Solar's proven *SoLoNOx* technology, which is capable of operating over a wide load range, or a diffusion-flame combustor adapted from Solar's proven *Mars* gas turbine. Both combustor options are capable of operating on natural gas. Additionally, the *Titan* 130 single-shaft can also operate on liquid fuel.

The *Titan* 130 gas turbine design is an aerodynamic scale of the existing *Taurus* 70 product. The unit features a modified *Mars* air compressor and turbine section components directly scaled from the *Taurus* 70, resulting in a low-risk product design well-suited for industrial service applications. A major element of the development strategy included 8000 hours field evaluation of the two-shaft version of the *Titan* 130, which has common components with the single-shaft engine. With over 100 *Titan* engines tested, and most in service, the engine/package has proven to be effective for power generation and mechanical drive applications.

This paper discusses the evolutionary design of the *Titan* 130 from the *Taurus* 70 and *Mars* gas turbine products, design details of the single and two shaft engines, the field evaluation program of the two-shaft *Titan* 130 and general field experience of many engines in service.

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AUTHOR BIOS

MARTIN HABEL is a 16 year employee of Solar Turbines Incorporated with broad experience across the organization. He is currently the Manager of Product Strategy for the Oil & Gas organization within Solar. His main responsibility is strategy development for new turbo-machinery products as well as product improvements. Previously, Martin was the Package Product Manager for Oil & Gas Generator Sets. Other positions he has held include Manager of Applications Engineering for North America, Manager of Enclosures and Ancillary Design, and Senior Project Manager. Martin has a Bachelor of Science in Mechanical Engineering from San Diego State University and is also a licensed Professional Engineer in the state of California.

RAINER KURZ is manager of Systems Analysis and Field Testing for Solar Turbines Incorporated in San Diego. His organization is responsible for equipment selection in the business development phase including the prediction of gas compressor and gas turbine performance, conducting application studies, and for field performance tests on gas turbine driven compressor and generator packages. Dr. Kurz attended the University of the Federal Armed Forces in Hamburg, Germany, where he received the degree of a Dipl.-Ing., and, in 1991, the degree of a Dr.-Ing.. He joined Solar Turbines in 1993 and is a member of ASME since 1992. He has authored numerous publications in the fields of turbomachinery and fluid dynamics, and was the presenter in a number of gas turbine related tutorials.

GEORGE ROCHA is Group Manager of New Product Design Engineering and has been employed at Solar Turbines Incorporated for over 16 years. He has held positions in Design, Engineering Management and Customer Services International Project Management.
His most significant accomplishments are Technical Team Leader for development of the Taurus 70 and Titan 130 HED Gas Turbines. Mr. Rocha graduated from California Polytechnic State University - San Luis Obispo with Bachelor Science in Mechanical Engineering.

MOHAMMAD SAADATMAND is Group Manager of the Titan Program and has been employed at Solar Turbines Incorporated for the past 13 years. His main responsibility is to manage the design, development and production support of the Titan program. He has held position in Aero-Performance group as an aerodynamicist responsible for the T70 and Titan compressors. He also worked at Alstom (a. k. a. Ruston Gas Turbine) in Lincoln, England for three years as an aerodynamicist, working on the design and development of the Typhoon and Tornado compressors. Mohammad has Bachelor of Science in Mechanical Engineering from Sunderland University and Master of Science in Gas Turbine Technology from Cranfield University.

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INTRODUCTION

Solar Turbines Incorporated has developed the *Titan* 130 industrial gas turbine engine in response to increasing application demands for higher performance industrial turbomachinery products in the 10-to-15 MW size range. The simple-cycle, 14 MW class machine represents the largest gas turbine in Solar's family of turbomachinery products and is available in single and two-shaft configurations, see Figure 1. Initially, the two-shaft version was introduced in 1998, for industrial service in gas compression and pump-drive applications (Rocha, etal 1998)and is now rated at 19,500 hp with over a 35% efficiency. The *Titan* two-shaft engine was then converted into a single-shaft engine for electrical power generation applications, with ISO rating of 14.25 MWe and 35.0% efficiency at the generator terminals. The conversion primarily included removal of the power turbine and accessory drive and the addition of a third stage shrouded turbine and gearbox.

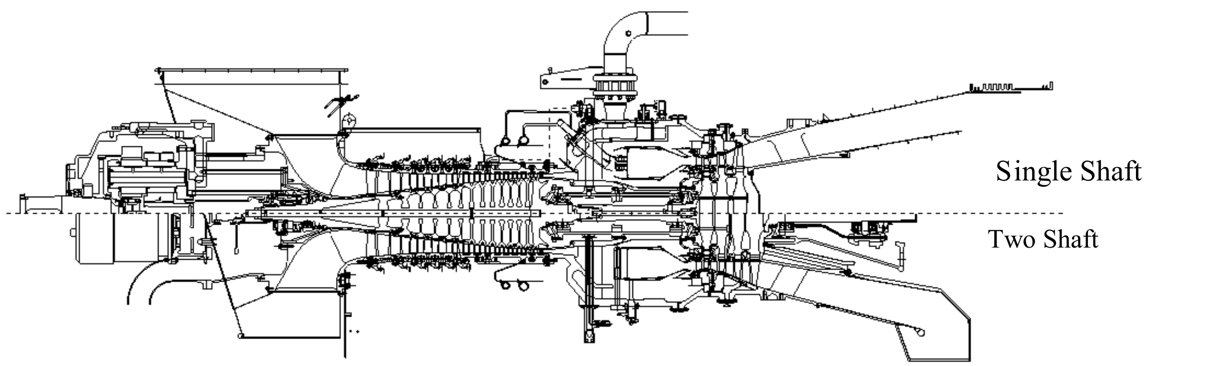

Figure 1. Titan 130 Single and Two Shaft Gas Turbine

Using Solar's traditional development strategy of product evolution, the *Titan* 130 gas turbine design incorporates proven technology and design features for rugged, durable industrial service operation with minimal life-cycle costs. The gas turbine operating-cycle and overall aerodynamic design is similar to the 7-MW size class *Taurus* 70 gas turbine introduced in 1995 (Rocha, etal 1995). Proven aerodynamic scaling techniques were implemented to establish flow path and airfoil component designs from the smaller *Taurus* 70 turbine. Thus, the basic design of the *Titan* 130 gas turbine features components directly scaled up from the *Taurus* 70 as well as hardware common to the 11 MW size class *Mars* gas turbine, see Figure 2. As with the *Mars* and *Taurus* 70 gas turbine products, the *Titan* 130 gas turbine also includes a lean-premixed, dry low pollutant emissions combustion system based on Solar's *SoLoNOx* technology and demonstrated operating experience.

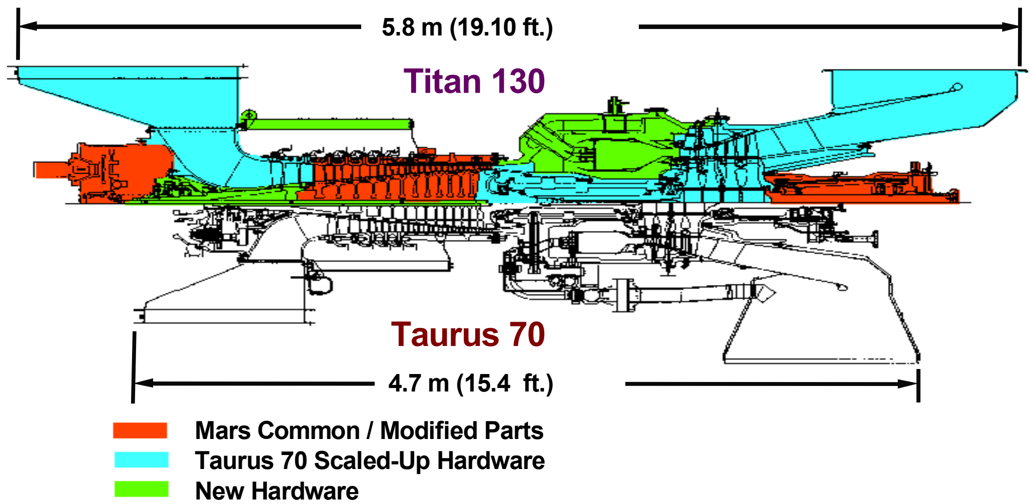

Figure 2. Titan 130 / Taurus 70 Two-Shaft Gas Turbine Comparison

As part of the standard product development process, a comprehensive field evaluation program was conducted at a gas compression installation to assess design durability under actual operating conditions.

The two-shaft version is intended for industrial service in gas compression and pump-drive applications. The single-shaft version is available as a generator set package for electrical power generation.

Titan 130 Aerodynamic Scaling

Based on the exceptional aerodynamic performance and successful introduction of the *Taurus* 70 gas turbine, concept studies for the *Titan* 130 gas turbine focused on maintaining similar operating cycle parameters of firing temperature (1150°C) with a 17:1 pressure ratio for the single-shaft and 16:1 pressure ratio for the two-shaft version. Because of the aerodynamic similarity between the *Taurus* 70 and *Mars* compressors, evaluations determined that the newly designed *Taurus* 70 00-stage could be scaled up and added to Stages 1 through 13 of the *Mars* compressor. Similarly, using scaled-up versions of the well-proven *Taurus* 70 two stage gas generator turbine and the newly designed third stage shrouded turbine reduces product development risks on performance, cost and schedule.

As described in the previous section, Solar has successfully utilized aerodynamic scaling and zero-staging techniques to enhance or expand its gas turbine product line, while preserving the general design philosophy of product evolution from proven technology and operating experience.

Using an aerodynamically scaled flow path with identical operating cycle parameters of pressure ratio and firing temperature would result in comparable gas temperatures and pressures throughout the compressor and turbine sections. The larger rotating and stationary components, while maintaining identical design features, cooling flows and delivery schemes, and reduced rotational speeds, result in identical mechanical stress conditions at comparable metal temperatures. Implementing a gas turbine design strategy based on aerodynamic scaling greatly reduces analytical efforts and technical risks, as well as enables the application of test results and operating experience gained from an existing gas turbine product.

GAS TURBINE PERFORMANCE

The selected operating cycle for the *Titan* 130 gas turbine was influenced by the design approach to aerodynamically scale the *Taurus* 70 gas turbine and use identical cycle parameters of pressure ratio and firing temperature. Using *Taurus* 70 gas turbine operating cycle parameters, component efficiencies, cooling/leakage flow rates at a larger aerodynamic design scale produced the design intent performance. In addition, using a proven aerodynamic design and operating cycle, successfully demonstrated with the *Taurus* 70 gas turbine, satisfied the program strategy of minimizing product development risk, cost and time.

The *Titan* 130 single-shaft gas turbine cycle incorporates a 17:1 pressure ratio at a maximum turbine rotor inlet temperature (TRIT) of 1150°C with a mass flow of 48.0 kg/sec to achieve the desired performance rating. The measured output performance with no inlet and exhaust losses for the single-shaft gas turbine over a range of ambient operating conditions is shown in Figure 3 and Table 1. At ISO operating condition, the *Titan* 130 with a measured efficiency of 35% at terminal is considered the most efficient industrial designed gas turbine in this class size.

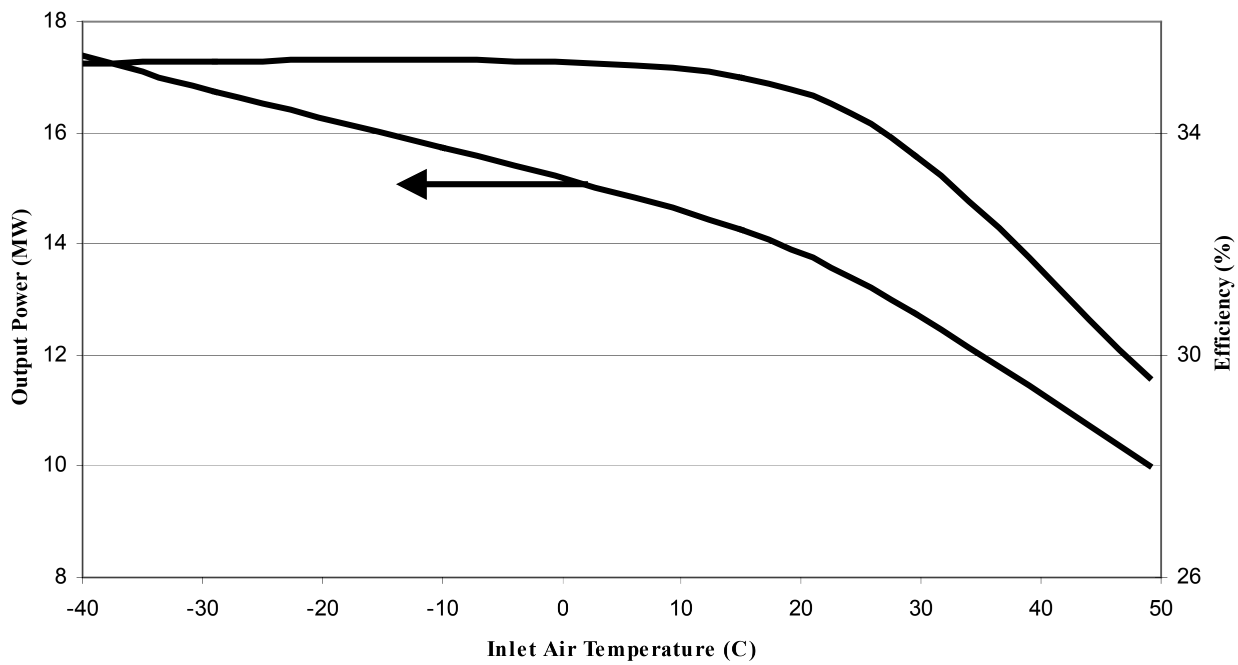

Figure 3: Titan 130 Single Shaft Performance Characteristics

	Taurus 70 CED	*Titan* 130 CED
Power (MW)	7.3	14.25
Efficiency %	33.8	35.0
TRIT °C	1150	1150
Speed (RPM)	15200	11220
Exhaust Temp °C	493	493
Air Flow (Kg/s)	26.7	48.0
Pressure Ratio	17:1	17:1
Nox/CO/UHC, ppmv (Gas)	25/50/25	25/50/25
Nox/CO/UHC, ppmv (Lq)	96/50/25	96/50/25

Table 1: Single Shaft Engine Performance Parameters

The two shaft *Titan* 130 gas turbine design cycle consists of a 16:1 pressure ratio at a maximum turbine rotor inlet temperature (TRIT) of 1150ºC (2100ºF) with a mass flow of 48 kg/s (106 lbs) to achieve the design performance rating. The predicted output performance, with no inlet and exhaust losses, for the two-shaft gas turbine over a range of ambient operating conditions and output speeds is shown in Figure 4. The power turbine is designed to deliver optimum power at a rated speed of 7900 rpm and can operate up to a maximum continuous design speed of 8855 rpm in direct-drive applications. Table 2 shows the predicted ISO performance and design parameters at the design rating with a comparison to the Taurus 70 and Mars 100 two-shaft gas turbines.

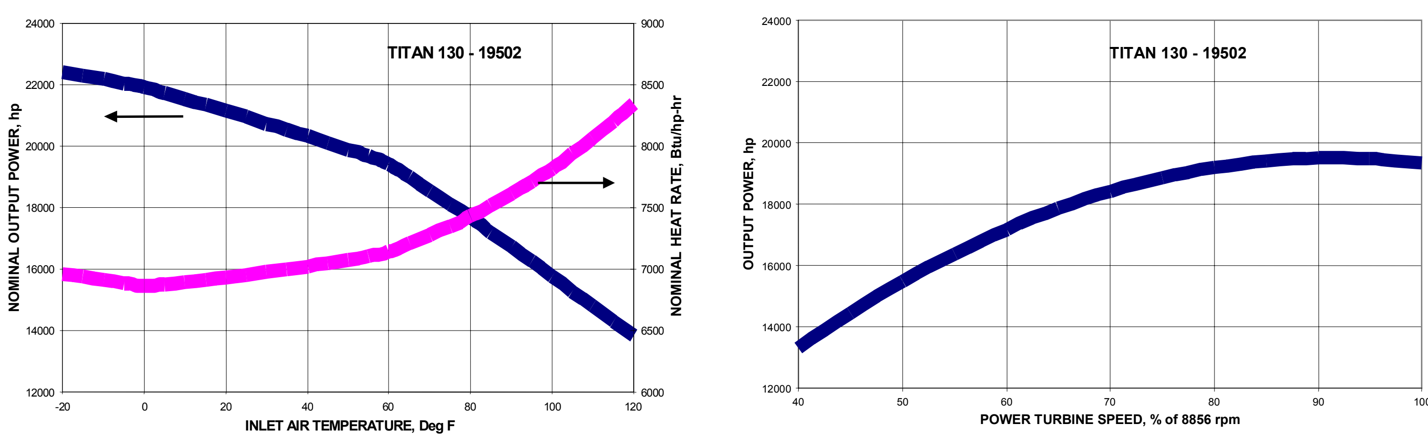

Figure 4. Titan 130 Two-Shaft Gas Turbine Performance (ISO Conditions)

Rating	Mars 100	Taurus 70	Titan 130
MW (hp)	11.2 (15,000)	7.7 (10,310)	14.5 (19,500)
Efficiency, %	34.0	34.8	35.7
TRIT, °C (°F)	1121 (2050)	1150 (2100)	1150 (2100)
GG Turbine, rpm	11,168	15,200	11,220
Power Turbine, rpm	9230 (9500 max.)	10,800 (12,000 max.)	7970 (8856 max.)
Exhaust Gas Temp., °C (°F)	485 (905)	495 (920)	490 (915)
Airflow, kg/s (lb/s)	42 (91.6)	26.6 (58.5)	48 (105.2)
Pressure Ratio	17.2:1	16.5:1	16.4:1
NOx / CO / UHC, ppmv	25 / 50 / 25	25 / 50 / 25	25 / 50 / 25

Table 2. Titan 130 Two-Shaft Gas Turbine Performance Parameters

GAS TURBINE – SINGLE-SHAFT MODEL

Compressor

The *Titan* 130 air compressor assembly represents a scaled-up version of the 14-stage *Taurus* 70 axial air compressor. As described previously, the 14-stage *Titan* 130 air compressor consists of the *Taurus* 70 forward compressor stage directly scaled to match 13 existing stages from the *Mars* air compressor. Rotor design speed for the larger *Titan* 130 air compressor was slowed to 11,220 rpm, using the inverse of the scale factor, from the *Taurus* 70 gas generator speed of 15,200 rpm to match the original design speed of the *Mars* compressor rotor.

The scaled-up forward stage is characterized by a low aspect ratio, wide-chord airfoil design. *U*se of wide-chord airfoil design manufactured from forged materials results in a robust compressor blade with ample mechanical strength for greater tolerance to ice ingestion in cold-ambient operating conditions. Self-aligning, curvic coupling teeth are used to mate the forward-bladed disk assembly to a welded-drum rotor assembly from the *Mars* gas turbine Stages 1 through 13. Common *Mars* compressor blades are manufactured from high strength, corrosion-resistant, nickel-based alloys using forged and investment cast processes. They have demonstrated component durability with millions of hours of service in adverse industrial operation. Similar to the *Mars* gas turbine, all compressor blades can be removed from the welded-drum rotor for cleaning or repair without major gas turbine disassembly. The entire rotor assembly, including a forward cone and aft-hub shaft, is held securely together with a solid centerbolt threaded into the aft-hub shaft and stretched with a centerbolt nut at the front end of the forward cone. The compressor rotor assembly features trim-balance capability successfully demonstrated with the *Taurus* 70 rotor. Balance planes at the forward and aft ends of the rotor have been established and are accessible through ports in the housings to facilitate trim-balance correction of synchronous vibration levels in field service environments without disassembly.

Similar to the *Taurus* 70 and *Mars* gas turbines, the vertically split case design allows greater access to flow path components for inspection, cleaning or service. Due to exit flow temperatures, a separate aft compressor case manufactured from stainless steel, similar to the *Mars* gas turbine, is required. Both forward and aft cases feature dedicated borescope ports for internal inspection of blades and stators. A compressor bleed port is located on each side of the aft case for extraction of interstage bleed air from the eighth-stage for turbine cooling and seal buffering. The forward case, manufactured from cast ductile iron, contains the variable geometry stator vanes common to the *Mars* compressor. Unison rings around the case actuate the variable vanes simultaneously via lever arms attached to each vane stem. The unison ring actuation system features an electromechanical linear actuator with a built-in feedback positioner for improved position response and accuracy. Six rows of variable stator geometry help provide sufficient surge margin for the gas turbine during normal start-up. The compressor variable geometry stator vanes are also used at part-load operation in order improve emission levels.

Combustion System

The *Titan* 130 gas turbine was introduced with a dry, low emissions combustion system based on Solar's proven *SoLoNOx* pollution-prevention combustion technology. The lean-premixed combustor is capable of reducing nitrous oxides (NOx) and carbon monoxide (CO) pollutant emissions to levels of 25 ppmv and 50 ppmv, respectively, over a wide load range.

The in-line, annular combustor is situated between the compressor and turbine assemblies within the gas generator module (Figure 5). The combustion system features 14 lean-premixed gas and dual fuel injectors similar in design to the *Mars 100* and *Taurus* 70 injectors and a combustor liner with advanced impingement/effusion cooling technology.

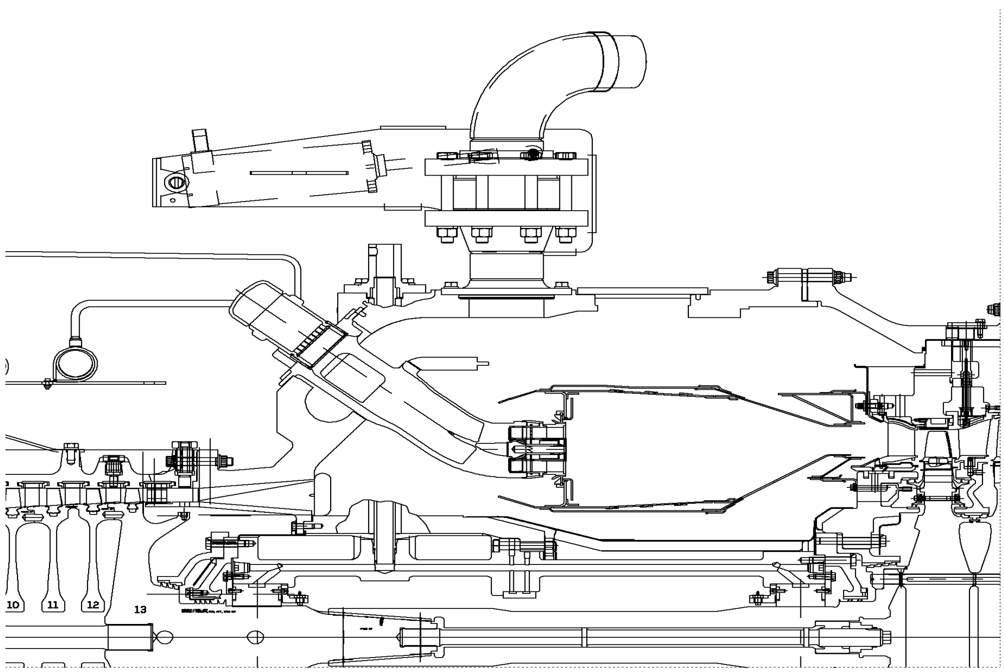

Figure 5: Titan 130 SoLoNOx Combustion System

A diffusion-flame, conventional combustor is also available and has been integrated into the gas generator module with no changes in rotor shaft or overall engine length relative to the *SoLoNOx* version (Figure 6). Maintaining Solar's philosophy of product evolution from proven designs, the *Titan* conventional combustion system has been adapted from the *Mars* conventional combustion system by incorporating identical fuel injectors, ignition torch and modified combustor. Twenty-one fuel injectors are mounted in the same *Mars* arrangement and engage the same *Mars* dome assembly of the combustor liner. Combustor liner outer and inner wall exit panels were modified to match the inlet diameter geometry of the larger *Titan* flow path. Cooling scheme enhancements were implemented based on factory development testing and *Mars* operating experience to optimize combustor performance and liner metal temperature patterns. With common fuel injectors, the *Titan* 130 can operate on a wide range of gaseous and liquid fuels currently offered on the *Mars* product. The *Titan* 130 combustion system is the same for the single and two-shaft models.

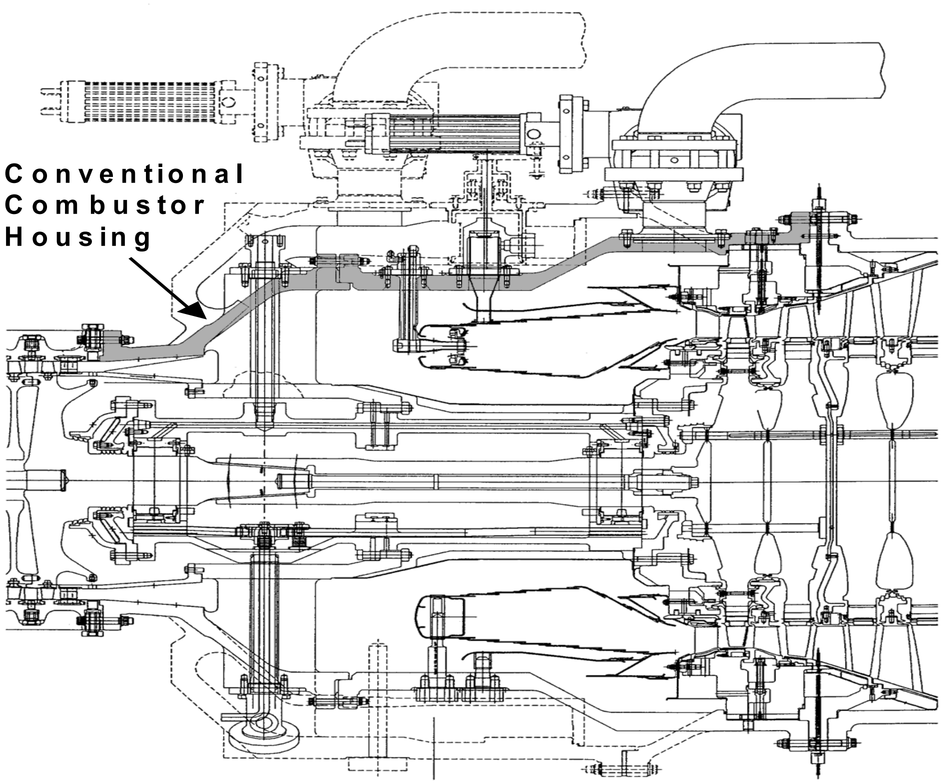

Figure 6: Titan 130 Conventional Combustion System

Turbine Section

The three-stage high-pressure turbine driving the air compressor and electrical generator load is scaled directly from the smaller *Taurus* 70 turbine with identical detail component designs, cooling schemes and material selections. Nozzle vanes and the first-stage turbine blades are internally cooled with compressor discharge air delivered internally within the gas turbine. Turbine cooling technology and design specifications used were derived from *Mars* gas turbine development and operating experience and verified through extensive component development testing during the design phase of the *Taurus* 70 gas turbine.

All the turbine blades are investment cast from high strength, nickel-based superalloys with protective diffusion-aluminide coatings for corrosion/oxidation resistance being applied to the first two stages. Cooling air for the first-stage blade and disk root attachments is supplied to the rotor by a first-stage diaphragm/preswirler delivery system. Forward and aft disk rim seals are used on the first-stage rotor to meter cooling airflow rates into the main gas path and minimize hot gas ingress along the inner hub region. The aft side of the second stage disk and forward face of the third stage disk is cooled using the compressor bleed air delivered internally.

In the 1st and 2nd stages of the turbine, the blades have under-platform friction dampers/seals between adjacent blades to dissipate vibration energy and to seal hot gases from the blade root attachments. The third stage blade is shrouded for better tip clearance control, leakage flow reduction and blade vibration damping. The three disks are assembled via curvic coupling interface with high strength through-bolts for increased clamp load and torque capacity. An important tip-clearance control feature, demonstrated with the *Taurus* 70 design, allows tight tip clearances to be set and maintained through transient and steady-state operations, including hot restart conditions. Independent nozzle support rings for each turbine stage have been sized to match the thermal response of the rotor disks during transients. This design characteristic and use of blade tip seals faced with abradable coating minimizes occurrences of tip rubs ensuring optimum output performance. All three individual nozzle support ring assemblies can be installed and removed in modular form to simplify gas turbine assembly and disassembly. The module design configuration enables the turbine disk assemblies and nozzle support ring assemblies to be horizontally removed from the gas generator as a bundle with proper field tooling. Removal of the turbine bundle and diaphragm/preswirler assembly enables access to the combustor liner for inspection and/or repair in field service environments. The third stage nozzle assembly also provides the structural support for the axial discharge cast exhaust diffuser. Thus the axial diffuer is designed and sized for optimum aero-performance recovery with minimal losses. The two diverging inner and outer walls of the exhaust diffuser are held together through one set of airfoil shaped struts. The engine thermal's axial expansion/contraction is compensated by a flexible bellows.

GAS TURBINE – TWO-SHAFT MODEL

The two-shaft version of the *Titan* 130 gas turbine is a direct scale of the smaller *Taurus* 70 two-shaft gas turbine and features components common to the *Mars* gas turbine. The basic layout consists of independent gas generator and power turbine modules close coupled in a traditional axial configuration similar to current *Solar* gas turbine products. This typical design configuration with modular construction, as demonstrated with the *Taurus* 70 gas turbine, makes the *Titan* 130 gas turbine well suited for rugged industrial service and provides easy access for field inspections and/or scheduled maintenance. To facilitate field service, the machine incorporates 60 borescope access ports for inspection of internal flow path components. A vertically split compressor casing design enables removal of either case half for greater access to internal compressor components for inspection and cleaning or service.

Similar to the *Taurus* 70 gas turbine, the gas generator module incorporates a 14-stage axial compressor (derived from the *Mars* air compressor) driven by a two-stage, high-pressure turbine aerodynamically scaled up from the *Taurus* 70 gas turbine. The gas generator rotor is supported by three, fluid-film, tilting-pad journal bearings with a tilting-pad thrust bearing located at the forward end of the compressor for ease of access in field service environments.

The rugged, structural shell of the gas generator module consists of the radial air inlet, compressor, compressor diffuser and turbine support housings. The *Titan* 130 gas turbine features the integral accessory-drive gearbox assembly from the *Mars* gas turbine and is flange mounted to the front face of the scaled air inlet housing for optional gas turbine-driven hydro-mechanical systems.

The power turbine module is a direct scale-up of the *Taurus* 70 power turbine assembly, featuring a two-stage axial turbine design, delivering the output power across a broad operating speed range. The independent module is flange mounted to the aft end of the gas generator module turbine housing in a close-coupled arrangement. The two modules can be separated in the horizontal position requiring less than 50 mm (2 in.) of axial disengagement distance for lateral clearance between modules. This minimal disengagement distance between modules facilitates removal/replacement of either module assembly from either side of the turbomachinery package skid. Two tilting-pad journal bearings support the power turbine rotor in a overhung arrangement with a tilt-pad thrust bearing located at the output end of the rotor shaft. An enhanced version of the *Mars* power turbine bearing housing has been adapted to the *Titan* 130 power turbine module. The exhaust collector redirects exhaust flow radially outward and can be rotated in various circumferential orientations to accommodate installation requirements. An interconnect-shaft system with a dry, flex-type coupling is used to couple the power turbine rotor shaft to the driven equipment.

GEAR BOX FOR SINGLE-SHAFT MODEL

The reduction gear train is a compound star arrangement with three equally spaced star clusters. The power flows through the sun gear, into three first stage gears, through three second-stage pinions and to the ring gear on the output shaft. With the exception of the ring gear, the power train gears are made of SAE 9310 Vacuum Arc Remelt Steel. The input stage gears are double helical gears. Double helical gears with opposite angles compensate the thrust loads induced from helix angle. Thrust bearing and more than thirty components are eliminated when comparing with the construction of single helical input gears.

The countershaft gear clusters have two sleeves bearings mounted inside the gear bores. This type of gear mounting minimizes the shaft length, thereby reducing the structure and shaft deflections. Another advantage is that all 360° of the bearing circumference are utilized to carry the load, instead of just one local area.

OFFSHORE POWER GENERATION APPLICATION

An interesting feature of the single shaft *Titan* 130 engine and package design configuration is that the system is capable of utilizing an axial exhaust duct, as is customary with most cold end drive engines, as well as radial exhaust duct with minimum hardware changes. The system essentially utilizes a short cast diffuser that is common to both axial and radial configuration. Inner and outer sheet metal cones complete the axial design and the two-shaft *Titan* 130 collector is used for radial design configuration. The radial exhaust configuration was designed in order to minimize the package total installed length for offshore application as compared to additional length required for an axial ducting and silencer. Figure 7 illustrates the *Titan* 130 axial and radial exhaust configurations.

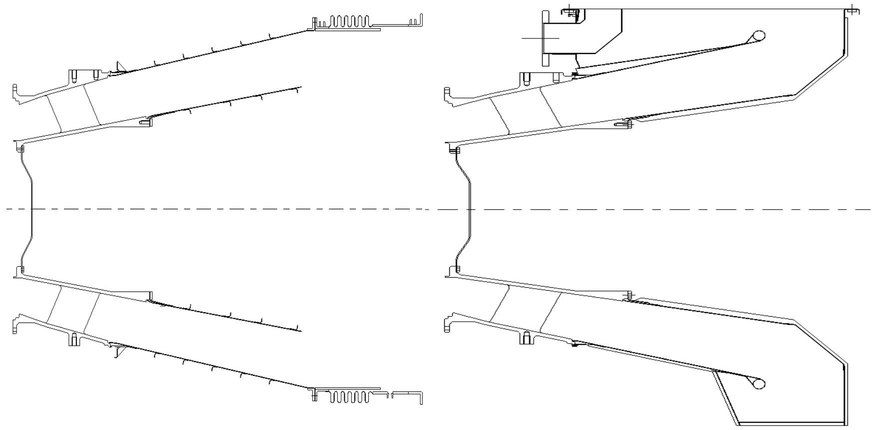

Figure 7: Titan 130 Single Shaft Axial and Radial Diffuser

PACKAGE AND CONTROLS – POWER GENERATION

The Titan 130 single shaft package consists of driver and driven frames, with a total length of 14020 mm. The package width is 3048 mm rail-to-rail and the unenclosed height is 3239 mm. The frames are based upon the Mars and Centaur/Taurus family of frames. It is based on 752 mm I-beams, in a ladder style construction. A 3407 liter lube oil tank is an integral part of the frame, with full package drip pans. A complete, unenclosed package, filled with nominal 3407 l of lube oil, and with a typical open drip proof generator weighs about 69,500 kg. The fully enclosed package weight, with lube oil, is about 83,500 kg. The package footprint is designed to provide a compact installation, with access for equipment maintenance. The two piece frame design allows more flexibility for shipping than a single, 14020 mm skid.

Lube Oil System

An engine driven lube oil pump supplies oil to the engine, gearbox and generator at a maximum flow rate of 1317 l/m. A separate pre-post lube pump is driven by a 5.6 kW AC motor. A smaller backup lube pump is driven by a 0.75 kW DC motor, and is powered by the 120 VDC battery system. It provides lubrication to the "hot" bearings only in case of an AC power outage.

Fuel Systems

The liquid and gas fuel modules are assembled separately as stand alone modules. They are installed in equipment areas on opposite sides of the package. Components are mounted above I-beam height for ease of removal or access for maintenance. The liquid fuel system, meters fuel via a variable speed controlled pump, driven by a 19 kW AC motor - the VFD is located off-skid. SoLoNOx gas fuel and standard combustion systems are available and use the PECC electronic fuel control valve.

Start System

The start system consists of twin direct AC start motors mounted on the reduction gearbox. A single, 300 kW VFD controls both start motors.

Control System

The package features an on-skid control system with an Allen-Bradley, programmable controller, flex input/output modules, and an Allen-Bradley color digital display. Turbine and generator controls are located on the driven skid. Generator controls include kW, kVAR, power factor, import and export control, auto synchronizing and load sharing.

Transient Response

In some power generation applications or island-mode operations, the fast response of an engine to on-load transient is of special interest to the end-user. Although most single shaft conventional combustion engines do offer fast response to transient on-load, engines with low-emission combustion system transient response is considerably reduced. This is because during part load low-emission operation the combustion system requires the engine firing temperature to be as close to the full load temperature as possible. The Titan 130 single shaft control systems have been optimized to increase the on-load transient capability during high-emission and low-emission modes, and reduced shaft speed recovery times. The optimization required new control algorithms, faster response electric actuators for the variable guide vanes and fuel valves and more accurate evaluation of turbine temperature response. The Titan 130 single shaft is now capable of taking full on-load at no-load with full speed recovery time of less than a few seconds. During low-emission operating mode, the engine can take up to 30% on-load.

Enclosure

The Titan 130 can have a driver-only enclosure or a full package enclosure, designed for 85 dBA sound attenuation, one meter away. The full enclosure is a drop-on style with bi-fold doors on both sides of the package for equipment access and engine removal. When the bi-fold doors are fully opened, the package sides are nearly completely open for access. Trolley rails are provided for internal equipment removal and handling. Engine removal is accomplished by an external structure and gantry crane off-skid.

PACKAGE AND CONTROLS – MECHANICAL DRIVE

The *Titan* 130 gas turbine mechanical-drive package design is based on the "ladder-frame" *Mars* gas turbine package (Rocha et al, 1998). A key feature of the *Titan* 130 gas turbine package design is the ability to mount a *Mars* gas turbine on the package for initial shipment, with the ability to upgrade to a *Titan* 130 gas turbine if the site power demand increases. The basic structure consists of a ladder frame constructed of 763-mm (30-in.) I-beams with a separate "drop-in" 8328-liter (2200-gal.) lube oil tank. The drop-in tank provides an economical means to incorporate an optional stainless steel tank when required. Package envelope dimensions of 9.75 m (32 ft) in length and 3 m (10 ft) in width rail-to-rail were selected for the driver skid to minimize installed space, provide good maintainability, and remain within practical shipping restrictions.

The mechanical-drive package is organized into separate areas, or equipment bays, for each package system to facilitate maintenance and service. System components requiring scheduled maintenance are mounted in the respective equipment bays to provide easy access. The gas turbine can be removed horizontally from either side without interference or additional removal of package system components located within the equipment bays beneath the gas turbine. All enclosure panels, support beams and fire protection system components can be removed with minimal effort to facilitate gas turbine removal.

Two start systems are available for the *Titan* 130 gas turbine: the direct-drive AC system, using a variable frequency drive (VFD), or a pneumatic system.

The gas fuel system is assembled separately and installed into the main package as a fully integrated system module. This system is greatly simplified, with primary components consisting of two shutoff valves and an all-electric servo motor-driven fuel valve. This system is easy to test, commission and maintain.

The lube oil system for the *Titan* 130 is available either as an all AC electrical system with pressure control by VFD motor control or as a gas turbine-driven primary pump system with a backup pre-post lube pump. In either case, a backup system to allow for safe gas turbine shutdown without damage is provided. The backup lube pump is driven by an electric motor powered by the DC battery system.

The package and gas turbine combination has been designed for all-electric control actuation, completely eliminating the need for a hydraulic servo system.

The control system is the newest generation of onskid programmable-logic control (PLC) now available to meet the Class I, Group D, Division 2 requirements of the National Electric Code and the Canadian Electrical Code. Optionally, an offskid PLC mounted in a control console is available for Class I, Group D, Division 1 applications and Cenelec Zone 1 or Zone 2 applications. Currently, an onskid PLC control for Class I, Group D, Division 1 applications is being designed. The onskid control greatly reduces interconnect wiring, requiring only a network cable and a limited number of wires to the operator / machine interface console. Maintenance is thus simplified, confining troubleshooting to the package area for each individual system.

A mechanical-drive package requires the successful marriage between the driver and the driven equipment. Most applications require a combination of high efficiency and high performance flexibility. Emphasis was placed on providing excellent gas compressor coverage for this product. The successful application of such a compression system is discussed and supported by site test data.

FIELD EVALUATION EXPERIENCE

Since the *Titan* 130 two-shaft engine was introduced into market ahead of the *Titan* 130 single-shaft, a field evaluation was conducted on the *Titan* 130 two-shaft, (Rocha, etal, 2001). The field evaluation test program was structured as a cooperative, commercial agreement based on a Solar engineering specification outlining inspection requirements and intervals during the first 8000-hours of operations. To provide optimum customer support for unplanned events, commercial provisions were added with onsite storage of serviceable engine and package components, field service tooling and availability of an exchange engine throughout the evaluation period. Solar's Engineering personnel conducted detailed inspections of the gas turbine and package systems per the planned intervals. Overall, the eight borescope inspections conducted throughout the evaluation period revealed no signs of early distress or damage indications. Results of each inspection were formally documented in a Solar engineering report and presented to the customer.

Date	Event	Comments
May 98	Shipped MD Package	Met Site Construction Schedule
Sep 98	Started Commissioning	High Vibrations with Driven equipment.
Nov 98	Gas Compressor Bearing Modifications	Marginal Improvement; Combustor Liner Inspected; Redesigned Gas Compressor Bearing Proposed
Feb 99	Gas Compressor Repaired	New Gas Compressor Bearings Installed
Mar 99	**Completed Commissioning**	
July 99	2000-hour Inspection	"Excellent Condition"; Improved Bleed Duct
Aug 99	Gas Compressor Repaired	Dry-Gas Seal Failure @ 2400 hours
Sep 99	3000-hour Inspection	"Excellent Condition"; Variable Guide Vane Seal Clearance Increased; Single Actuator Configuration
Nov 99	Power Turbine Change-out	Drive-Train Vibration Instability @ 3600 hours. Retest Normal
Feb 00	5000-hour Inspection	"Good Condition"; 100% Availability; Interconnect Shaft Replaced
Apr 00	7000-hour Inspection	"Good Condition"; 100% Availability
Jun 00	8000-hour Inspection	"Good Condition"; 100% Availability; Program Successfully Completed

Table 3: Field Evaluation Experience Summary

The 8000-hour evaluation period began once commissioning was complete and the unit placed in continuous commercial service. Table 3 provides a chronological summary of planned and unplanned events during the evaluation period. Initial delays in commissioning were attributed to operational issues with the vendor-supplied gas compressor. High rotor vibrations and high temperatures at the journal bearing under certain operating load conditions limited the operational range of the gas compressor. Troubleshooting efforts by the vendor ultimately led to a complete redesign and replacement of a journal bearing, which resolved the operational problem. In the early hours of operating experience, minor adjustments were required to fine tune the operation of package hydro-mechanical systems and control system display software. Operational data and feedback from customer operators and Solar's Field Service personnel were used to make adjustment to package components, wiring connections, controls system logic and display software parameters. A continuous emissions monitoring system (CEMS) supplied by Solar with exhaust-stack sensors provided real-time combustor emissions data used to fine tune

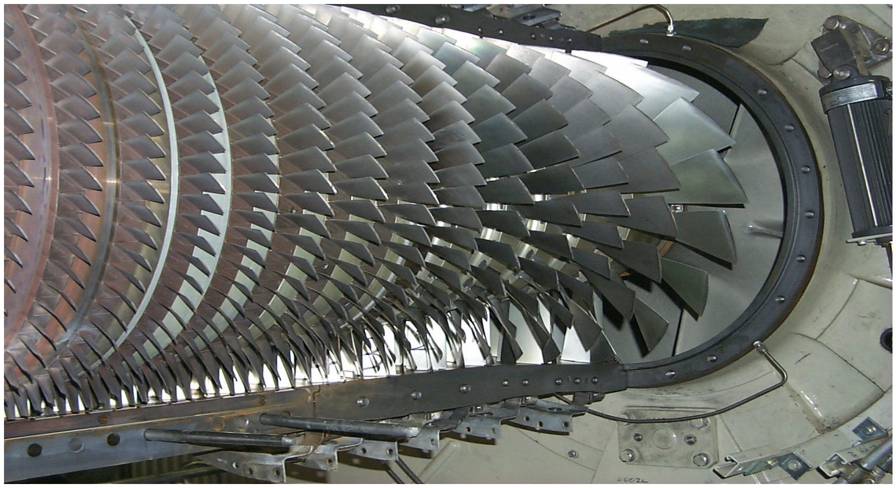

Figure 8: Field Inspection with Compressor Case Half Removed

controls system logic and algorithms to maintain NOx and CO emissions below guarantee levels at all ambient operating conditions.

At the 500-hour engine inspection, the heat-tint patterns on relatively clean metal surfaces of the turbine airfoils were reviewed and correlated to temperature exposure during operation. Tint patterns and flow path blade tip rub conditions were noted and provided a baseline condition for the gas turbine for future comparison. At the 2000-hour inspection interval, an improved bleed duct was installed with modifications to the inlet port of the exhaust collector. Upgrades were based on recent design improvements made on the *Mars* bleed duct system. An unexpected failure of the dry-gas seal system in the gas compressor, which occurred after 2400-hours of operation, was successfully repaired in the field by the manufacturer.

During the 3000-hour inspection, plans were made to remove the *Titan* 130 compressor case half for detailed flow path inspection and replacement of variable guide vane (VGV) inner seals (Figure 8). Since the initial engine shipment, additional factory testing was conducted to optimize VGV seal clearances to lessen wear grooves in the abradable seals and eliminate any potential for temporary rotor binding after engine hot restarts. The design improvement was incorporated into this field evaluation engine.

At the conclusion of the 8000-hour program, a comprehensive engine inspection was conducted by Solar's engineers to evaluate hardware condition and compare component oxidation patterns to baseline results recorded at the 500-hour inspection interval. Based on the excellent condition of the gas turbine and acceptable performance of the mechanical-drive package at the conclusion of the program, Solar and the customer jointly agreed to place the unit into normal commercial service in June 2000.

By the middle of 2003, over 104 engines have been ordered of which 68 are *Titan* 130 single-shaft engines for power generation or co-generation applications. Total operating hours on the *Titan* 130 are 304,000 hours. The two-shaft high-time unit has accumulated over 25,000 hours and the single-shaft high time unit has over 16,000 operating hours.

CONCLUSION

Since its recent introduction, the *Titan* 130 industrial gas turbine has gained market acceptance with more than 100 combined two-shaft and single-shaft units sold and placed into commercial service. The *Titan* 130 single-shaft is rated at 14.25 MW with 35% electrical efficiency at terminal at ISO operating conditions for power generation applications.

The two-shaft version is design rated at 14.5 MW (19,500 hp) with a simple-cycle thermal efficiency higher than 35% at ISO operating conditions. The package system is available in a mechanical-drive arrangement for gas compression and pump-drive industrial service applications. An integrated compressor-set package with a *Solar* gas compressor is also available.

Developed based on Solar's traditional design philosophy of product evolution from proven technology, the *Titan* 130 is an aerodynamic scale of the smaller *Taurus* 70 gas turbine. It features similar operating cycle parameters, scaled turbine components and a modified version of the *Mars* air compressor. Use of scaled and common hardware from Solar's proven products provides a low-risk design well suitable for rugged, reliable operation in industrial applications. The gas turbine has been thoroughly factory tested to verify output performance and mechanical integrity at all expected operating conditions. Product durability has been demonstrated with successful completion of an extended field evaluation program at a commercial installation. The *Titan* 130 mechanical-drive package was installed at a gas compressor station and operated by the customer under typical pipeline gas-transmission service conditions. In a cooperative agreement, the unit was frequently inspected and monitored throughout the evaluation period by Solar's Engineering and Field Service personnel to record operating condition and assess product durability. At the conclusion of the planned 8000-hour evaluation period, the gas turbine was thoroughly inspected and returned to normal commercial service with standard warrantee conditions. Although overall availability of the mechanical-drive package fell slightly short of the target set for the evaluation period, the unit was incident free and achieved 100% availability over the final 4500 hours of operation. Completion of the *Titan* 130 field test program provided early operating experience and verification of product durability characteristics in a typical industrial service application.

Furthermore, the *Titan* 130 gas turbine demonstrated Solar's capability to reliably provide complete systems, either by using generators, compressors or pumps from a variety of other manufacturers or by using gas compressors manufactured by Solar.

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