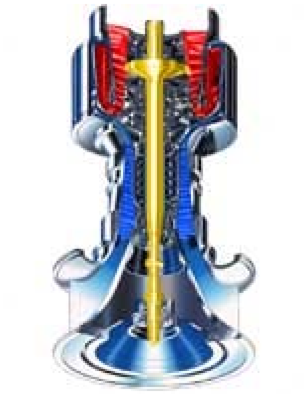
Development of the Vertical Gas Turbine

for a Vertical Pump Drive Application



Author: Tim Baur

Company: Vericor Power Systems

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About the Author

Tim Baur, Vericor Power Systems

Mr. Baur holds a Bachelor of Aerospace Engineering and Master of Mechanical Engineering from Auburn University. His experience includes system engineering for combined cycle power plants at Lockwood Greene, project and performance engineering at Mirant Corporation, and program management at Vericor Power Systems. He is a registered Professional Engineer.

Abstract

Vericor is the original equipment manufacturer of the TF™40/TF™50 and ASE™40/ASE™50 3-5 MW rated aeroderivative gas turbines. The flexibility of these gas turbine engines is utilized for marine propulsion, power generation, and mechanical drive applications.

Aeroderivative gas turbines provide a high power output with minimal volume and weight compared to their reciprocating engine counterparts. Turning an aeroderivative gas turbine in the vertical direction offers even greater space savings, which has been advantageous for flood control pumping applications with limited available space. With the successful implementation of the vertical gas turbine, this technology can be further examined for future use in power generation and mechanical drive systems for other space limited applications such as oil platforms.

This paper discusses development, application and technical challenges of transferring horizontally oriented gas turbine technology to a vertical configuration.

Table of Contents

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Introduction

The vast majority of gas turbines are horizontally oriented for reasons ranging from ease of maintenance to installation and application considerations. In particular, aeroderivative gas turbines are derived from horizontal thrust producing jet engines. The application of aeroderivative gas turbines for mechanical drive, power generation, and marine propulsion transferred conveniently to these horizontal systems.

Aeroderivative gas turbines provide a high power output with minimal volume and weight compared to their reciprocating engine counterparts. Reorienting an aeroderivative gas turbine in the vertical direction offers even greater space savings. This has proved advantageous for a recent application for flood control pumping stations that have limited available space. With the successful implementation of the vertical gas turbine, this technology can be further examined for future use in power generation and mechanical drive systems for other space limited applications such as oil platforms.

Background

In 1996, a Japanese customer expressed an interest in developing a vertical gas turbine for a vertical pump drive application. The intent was to replace large diesel engine drive pumps for flood control during the typhoon season.

The high volume of flood water produced by typhoons quickly fills low-lying areas and rivers in limited space areas of Japan. The local municipalities identified a need for a fast starting and high volume pumping system to quickly and reliably remove the flood waters from the affected areas. The limited available space in certain highly developed regions of Japan required a pump design that occupied a very small footprint, yet provided sufficient pumping power to remove the deluge of water from typhoons.

The customer tested two engine types with different power outputs to demonstrate the feasibility of the vertical gas turbine. A T53 gas turbine with a nominal output rating of 1200 kW (1609 shaft horsepower) and an ASE40 industrial gas turbine with a nominal output rating of 3,000 kW (4023 shaft horsepower) were tested in the parallel development of the vertical gas turbine. The T53 gas turbine was a legacy customer owned helicopter engine. The ASE40 gas turbine was a customer owned demonstration engine. The ASE40 was originally developed from T55 helicopter engine technology, and later from its closest relative, the TF40 marine propulsion engine. The ASE40 is currently applied to horizontal land based power generation and mechanical drive installations.

During the demonstration period, these gas turbines became known as the ASE15V and ASE40V, respectively. It was determined through minor modifications and testing that the vertical design was indeed feasible for both engine types. However, due to the production cancellation of the T53 engine, and since the customer had extensive experience in packaging, installing, and operating the ASE40 gas turbine in horizontal applications, the customer chose to move forward with the higher power ASE40 gas turbine for use in the vertical pump systems.

ASE40V Engine Characteristics

The ASE40V gas turbine is a highly modularized dual shaft gas turbine that provides a very high power to weight ratio. The ASE40V can start and accelerate from rest to maximum power in as little as 45 seconds. It weighs only 600 kg (1325 pounds) and produces up to 3,188 kW (4,275 shp) of uninstalled continuous duty shaft power. The combination of its compact modular design, light weight characteristics, and fast starting capabilities enabled the ASE40 engine to be the ideal candidate for vertical orientation.

The ASE40V is a cold-end drive gas turbine that incorporates a combination axial-centrifugal compressor driven by an axial two-stage turbine and independent two stage power turbine. Ambient air is drawn into the compressor through the radial inlet duct to provide smooth airflow into the seven-stage axial compressor. The compressed air discharges from the centrifugal compressor impeller into the combustor where the air is mixed with atomized fuel for the combustion process. Heat energy from combustion expands to provide work as the flow passes through the four turbine stages. The first two stages of the turbine section convert the high temperature gas-flow energy to mechanical shaft power to drive the compressor rotor and accessories. The last two stages provide power to the output shaft to drive the main reduction gearbox and pump shaft.

The ASE40V is comprised of the following four modular components as shown in Figure 1:

- Inlet Housing Module
- Accessory Gearbox
- Gas Producer Module
- Combustor and Power Turbine Module

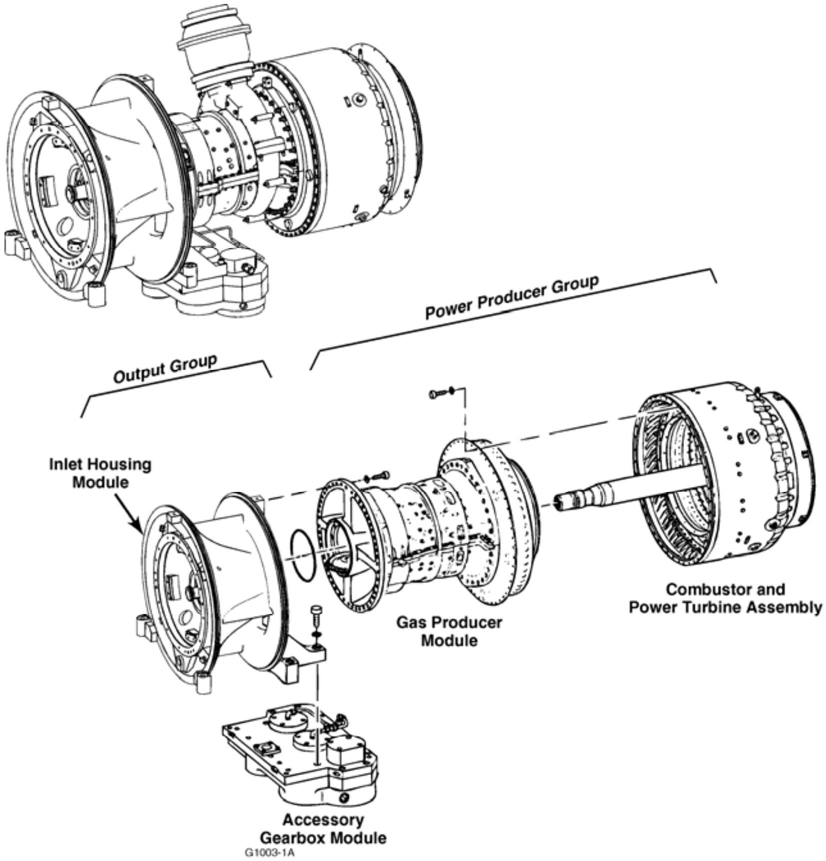

Figure 1. ASE40 and ASE40V Modular Components

To best explain the ease of converting the ASE40 engine to a vertical application, the following describes the engine's modular construction and key mechanical components. Figure 2 provides a cross sectional view of the ASE40V and identifies specific parts of each module.

Inlet-Housing Module

The inlet-housing module serves as the main support structure for the accessory gearbox module and the power producer group assembly. The output shaft is supported by the No. 6/7 bearing package and the inlet module and transmits power generated by the power producer group to the external load. The output shaft rotates at a speed of 15,400 rpm with a counter-clockwise direction of rotation relative to the inlet. Accessory power is transferred to the accessory gearbox module through the tower shaft.

Accessory Gearbox Module

The accessory gearbox module is attached to the side of the inlet-housing module and provides the drive mechanism for mounted accessories such as the lubrication and fuel pumps. It also houses the internal gearing and external mounting pads for the starter and power extraction for equipment provided by the turbine packager. A monopole speed pickup is protrudes through the casing of the accessory gearbox to measure the speed of the compressor and power turbine shaft.

Gas Producer Module

The gas producer module is comprised mainly of the compressor rotor assembly, compressor vanes, and gas producer turbine rotor and nozzle assemblies. The compressor rotor assembly is constructed of a seven stage axial compressor and a centrifugal compressor impeller mounted on a hollow shaft that is integral with the 3rd stage turbine. The compressor rotor assembly is supported at each end by the No. 1 and No. 2 bearings.

The No. 3 bearing is mounted in the inlet housing adapter assembly which also encases the accessory drive gear tower shaft and serves as the mounting flange that attaches the power producer group to the inlet housing module. A port is machined in the compressor housing to accommodate the air-bleed valve assembly that ensures a sufficient surge margin for the low-power operating range of the engine. The gas producer section compressor assembly compresses inlet air at a ratio of 8.8:1 at maximum continuous power and directs compressed air into the combustor chamber assembly.

Combustor and Power Turbine Module

The combustor and power turbine module includes a reverse-flow annular atomizing combustor chamber assembly and a two-stage axial-flow power turbine assembly. The power turbine shaft extends coaxially through, and in counter-rotation to, the compressor rotor assembly. This results in a front-end, or intake, drive. The power turbine shaft is supported by the No. 4/5 bearing package between the 3rd and 4th stage turbine rotors and is integral to the third turbine rotor. The output shaft engages splines at the forward end of the power turbine shaft for effective coupling to the main reduction gear.

The combustor chamber assembly attaches to the air diffuser assembly. The rear face of the combustor chamber provides support for the power turbine assembly, atomizing combustor, fuel manifold assemblies, and the fuel manifold fire-shield assembly.

Lubrication oil feed and scavenge tubes for the No. 4/5 bearing package pass through two vanes of the power turbine aft support. Exhaust gas temperature (EGT) thermocouple probes pass through the fourth-stage power turbine aft support and extend into the gas stream aft of the fourth turbine rotor to measure exhaust gas temperatures.

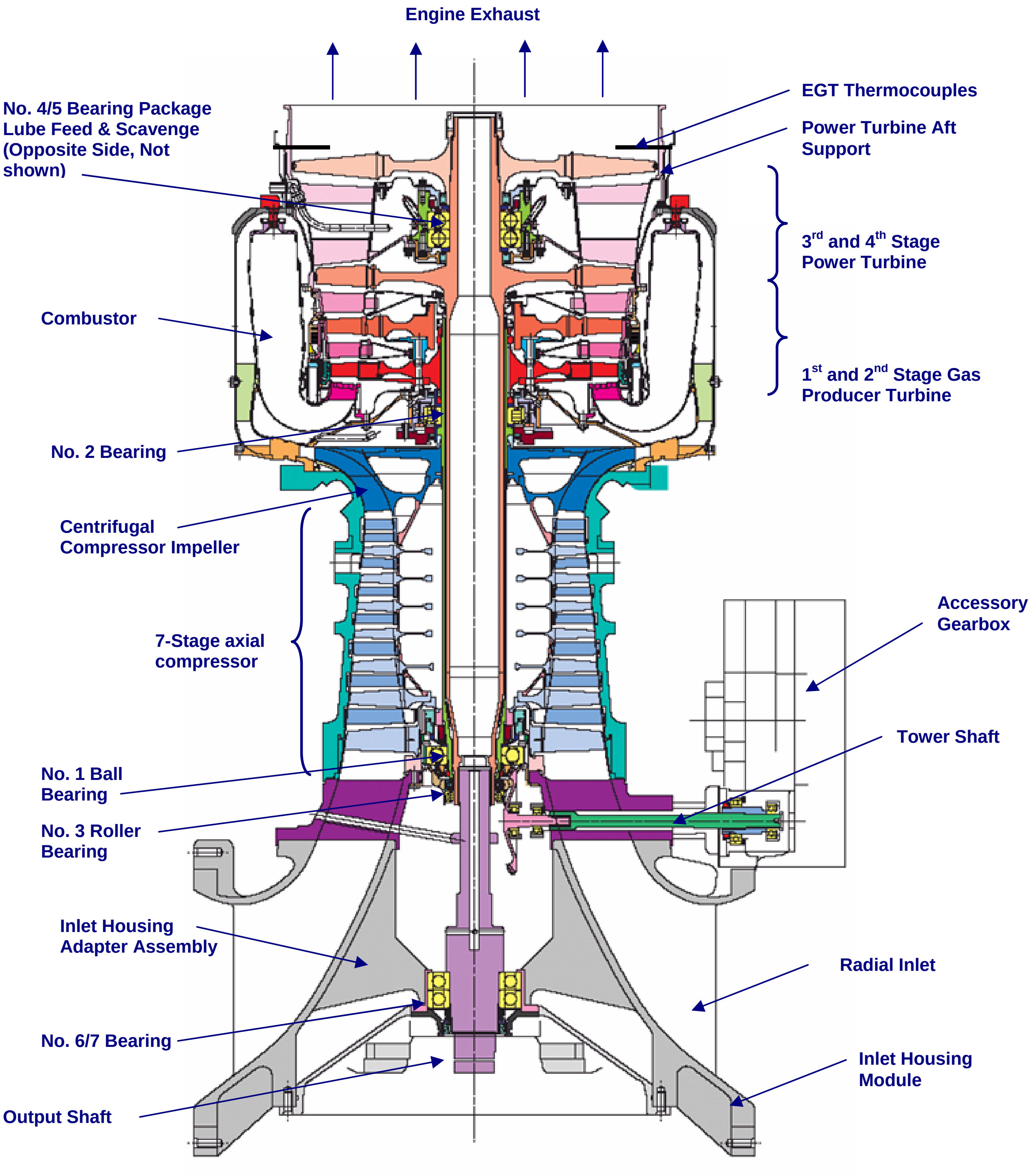

Figure 2. ASE40V Cross Section Components

ASE40V Starting and Control Characteristics

The ASE40V engine can be started by an AC or DC electric starter, an electro-hydraulic starter, or a pneumatic air turbine starter. The starter rotates the gas generator section through the geartrain as fuel is pumped through the fuel nozzles into the combustion chamber and ignited to accelerate the engine to idle.

An electrical DC starter is the most common starting method employed in the vertical pump application. The ASE40V can start and accelerate to 100 percent power turbine speed within 45 seconds.

The ignition system employs a dual-channel high-tension exciter, two ignition leads, and two igniter plugs. The electrical starter provides up to 136 Nm (100 ft-lb) of torque to the starter pad at various speeds and is designed to motor the engine for a minimum of 2 minutes at 1,200 rpm starter pad speed.

A digital electronic control system is used to control the ASE40V operation. It consists of a main control panel and an operator-interface display panel. The main control panel contains a PLC controller and associated signal conditioning and interconnection equipment to control the engine. All field electrical control devices interface with the PLC cabinet. The operator interface display panel contains the touch screen, operator-interface functions, turbine control display unit, the Emergency Stop button, and a warning buzzer. The two panels are connected via a single communication cable and a power/E-Stop control cable.

The ASE40V gas turbine operation is controlled by either the exhaust gas temperature governor or the power turbine speed governor. When the engine is operated below the maximum EGT of 599.4 C (1,111 F), the power turbine speed governor controls the speed corresponding to the desired power output set point. If operation causes the EGT to increase to the maximum set point, the EGT will be governed to the EGT limits for maximum continuous power settings.

The control system has two mechanisms to protect the engine from over-speed; 1) a topping governor that decelerates the gas generator, and 2) an over-speed shutdown that stops fuel flow to the gas generator. The over-speed set points are 100% power turbine speed for the topping governor and 107% power turbine over-speed shutdown. The output shaft over-speed limit is 17,000 rpm at which the automatic safety function will shut down the engine. The continuous torque limit is 2,847 Nm (2,100 lb-ft) which corresponds to the level recommended for the continuous duty operation capability of the engine. The maximum torque limit is 3,566 Nm (2,630 lb-ft) for transient operation of less than 5 seconds.

ASE40V Engine Performance

The ASE40V engine is capable of operation on gaseous methane, gaseous propane, No. 2 diesel fuel or kerosene. The most utilized fuel for the ASE40V application is No. 2 diesel fuel.

The engine is designed to operate satisfactorily over an ambient temperature range of -29°C to 54°C (-20°F to 130°F, up to 1800 meters (6000 ft) elevation and between 0 and 100% relative humidity. Operation below -29 °C is possible but requires heating of the engine oil and fuel.

The following chart provides various uninstalled performance parameters for maximum continuous duty using diesel fuel No. 2 diesel fuel at ISO conditions (15C, 60% relative humidity, sea level). The maximum continuous rating corresponds to the full time continuous operation allowed by the control system with no time limitation except as prescribed for inspection and maintenance intervals.

Characteristic	**Diesel Fuel No. 2**
Max Continuous Power	3,188 kW (4,275 shp)
Fuel Flow	958 kg/hr (2,109 lb/hr)
Heat Rate	12,771 kJ/kWh (12,108 Btu/kWh)
Exhaust Flow	12.78 kg/s (28.11 lb/s)
Exhaust Temperature	599.4 C
Efficiency	28.19 %
Pressure Ratio	8.8

Table 1. ASE40V Performance on Diesel Fuel No. 2

The net power delivered by the ASE40V is decreased by installation losses associated with the final packaged system. Installation losses include accessory induced loads and pressure losses attributed to inlet and exhaust system designs. Other factors that impact net power output include losses associated with the reduction gearbox, load device efficiencies, and engine performance degradation that accumulates over the operating life of the engine.

Figure 3 illustrates the nominal uninstalled power of a new ASE40V engine at ISO conditions and various fuel flow rates. The optimum power turbine speed line on each curve identifies the speed at which power turbine efficiency peaks, resulting in minimum fuel consumption for a given power.

The customer's vertical pump design required a wide range of gas turbine power capabilities that were specifically applied for each specific application. For instance, one application was designed for a flow rate of 825 cubic meters per minute (181,475 gpm) at a discharge head of 12.6 meters (41.3 feet) and a pump rotation speed of 280 rpm. This required a gas turbine output power of 2400 kW.

Another pump was designed for a flow rate of 1800 cubic meters per minute (395,945 gpm) at a discharge head of 3.2 meters (10.5 feet) at a pump rotation of 124 rpm, requiring 1,395 kW of power output. The flow rate for this application is equivalent to emptying a typical backyard pool in less than 4 seconds.

The ability of the ASE40V to operate at various power turbine speeds, coupled with the dual shaft design, provided the versatility required to accommodate a wide range of pumping power requirements.

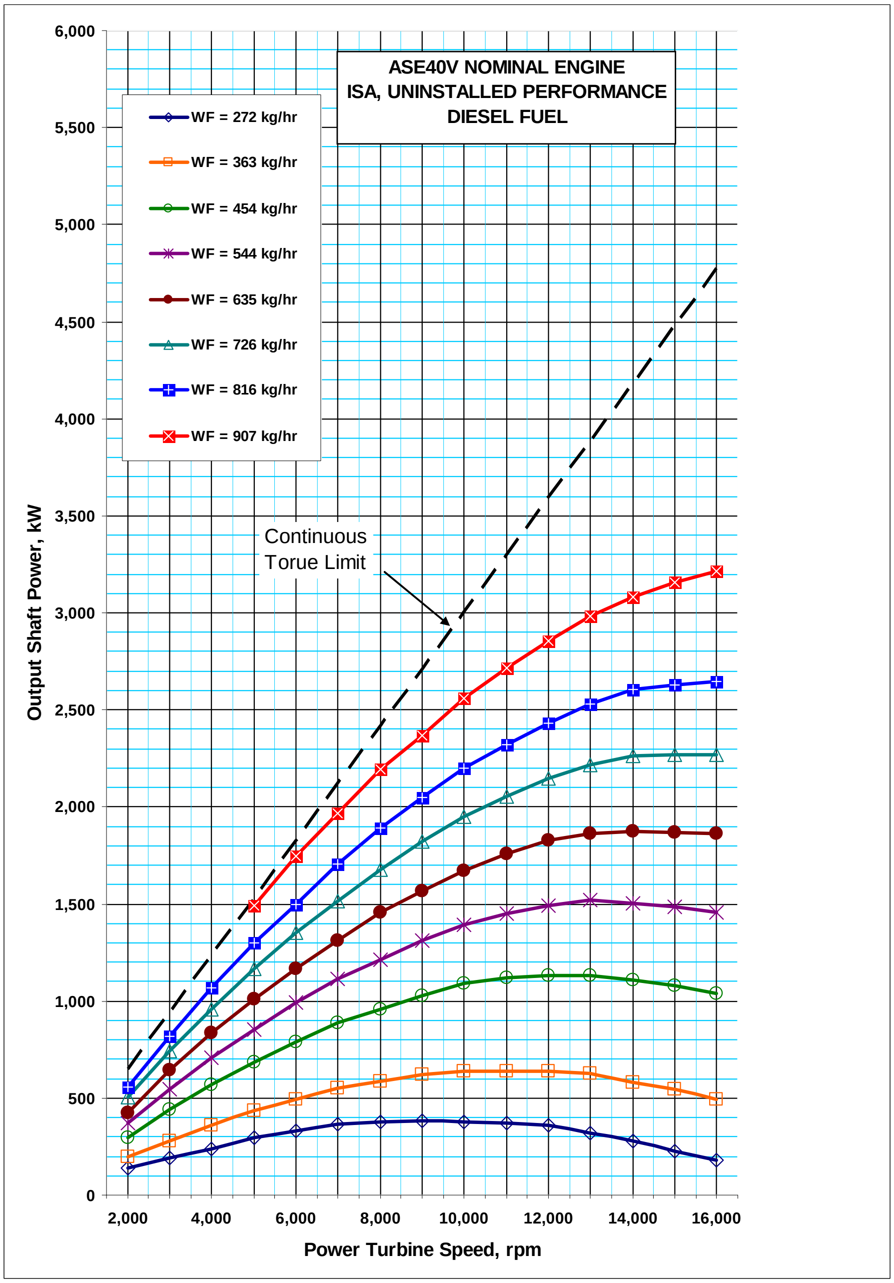

Figure 3. Engine Output Power versus Power Turbine Speed, Diesel Fuel.

Development of the Vertical Gas Turbine Configuration

The feasibility of the vertical gas turbine application was successfully demonstrated on both the ASE15V and the ASE40V. Each engine type had its own unique set of technical challenges to convert to a vertical orientation. The common primary concerns were pooling of fuel in the outer transition liner of the combustor and providing sufficient scavenging of lubrication oil from the accessory gearbox and the thrust bearing packages.

Certain events led to the understanding and need for minor configuration changes. In the demonstration testing of the ASE15V, the customer reported a sudden decrease in gas generator speed. In an attempt to rotate the gas generator through the starter spline, the gas generator locked up, yet the power turbine rotated freely. Subsequent attempts to rotate the gas generator revealed grinding and rubbing noise in the gas producer module. The gas turbine was subsequently disassembled and it was later determined that a fire had occurred in the area of the No. 2 bearing. The root cause analysis showed that excess fuel and oil pooled in the engine due to numerous wet motoring attempts, start attempts, and automatic shutdowns without subsequent light-off and operation at idle. It was apparent that the bulk of the damage was caused by burning of accumulated oil.

It was concluded that the small amount of fuel by itself would not have likely caused this type of failure. The fuel, however, contributed to the ignition of oil. Therefore, prevention of fuel and oil accumulation was determined to be the proper corrective action. This led to the following changes to the starting procedures and engine hardware:

- Minimize fuel accumulation by eliminating wet motoring and operation below idle
- Incorporate a lube scavenge pump for the No. 2 bearing for low speed operation during starts and shutdowns, similar to the ASE40V

An ASE40 development engine was also provided by the customer to jointly develop and test the vertical configuration. Similar to the ASE15V, the horizontal configuration was modified to include changes to the lubrication system in order to effectively scavenge the lubrication oil from the bearing cavities in the vertical orientation. The ASE40 gas turbine also required modifications to the accessory drive gearbox to reposition the lubrication oil ports to remove the oil lines from the inside of the inlet plenum.

After the minor modifications to the horizontal ASE40 development engine, a vertical demonstration test was conducted to evaluate the potential for bearing distress caused by the effects of thrust reversal on the No. 4/5 bearing and the potential for skidding of the No. 2 bearing. The test apparatus used for the vertical demonstration test is shown in Figure 4 below.

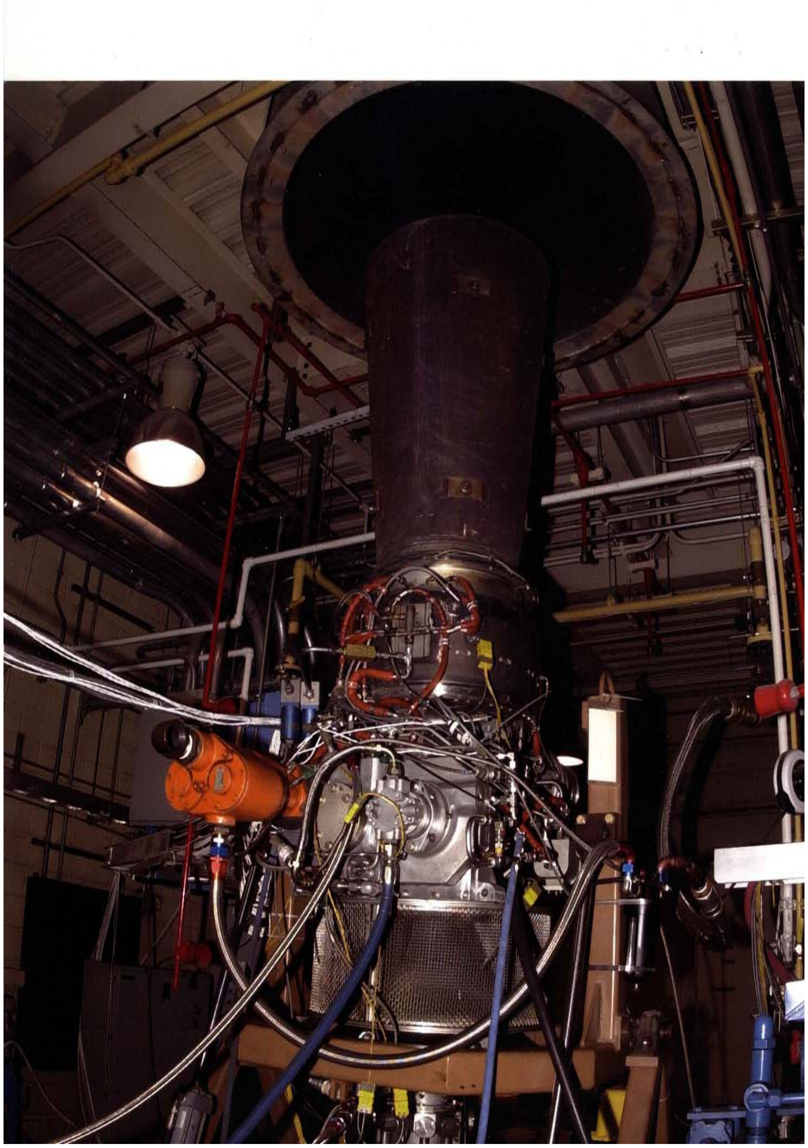

Figure 4. ASE40V Demonstration Test Apparatus

Additional test instrumentation and a thrust ring were fitted to the engine to measure the ball pass frequency for the No. 2 bearing and thrust values on the No. 4/5 bearing. This is the frequency that corresponds to the rate at which a ball passes a particular location on the inner and outer race of the bearing. It is useful for analyzing the spectra of engine vibration. The forward bearing passing frequency proved consistent with the horizontal test values for gas generator speed. It was concluded that there was no indication of skidding or slipping. Furthermore, the thrust data on the No. 4 /5 bearing was consistent with the horizontal testing values during startup.

A 75 hour durability test was conducted at the completion of the demonstration test and resulted in no reported anomalies. Later, a 50-cycle endurance test was conducted to verify the configuration changes to the lube scavenge system and to evaluate production hardware for distress caused by the vertical orientation. Each cycle consisted of the following sequence.

Start and Run Condition	**Run Time**
Start Initiation	-
Run Sequence	-
Idle	5 minutes
1,500 shaft horsepower	20 minutes
3,000 shaft horsepower	20 minutes
1,500 shaft horsepower	20 minutes
Idle	5 minutes
Shutdown	15 minutes

Table 2. ASE40V Endurance Test Cycle

Data taken during the endurance cycle testing and hardware inspection after disassembly concluded that, if installed and operated correctly, available ASE40 production hardware could be used with little to no risk in the vertical position. Another objective for the endurance test was to setup a vertical test cell to later be used for production testing. The endurance testing resulted in a total of 97 stars and 62 hours of operation.

Following the endurance test, the engine was disassembled and a visual inspection of the hardware was conducted to determine the acceptability for production. The inspection revealed no anomalies directly associated with the vertical orientation. The disassembled hardware was cleaned, reassembled, and later placed into service as the first vertical configuration.

Application of the Vertical Gas Turbine to the Vertical Pump

By using a vertically oriented gas turbine for the flood control pumping application, the customer was able to save between 24% and 40% of floor space. Below is a depiction of the installed space savings between a horizontal gas turbine compared to a vertical gas turbine. The space savings are even greater compared to a horizontal reciprocating engine installation, for which the vertical turbine replaced.

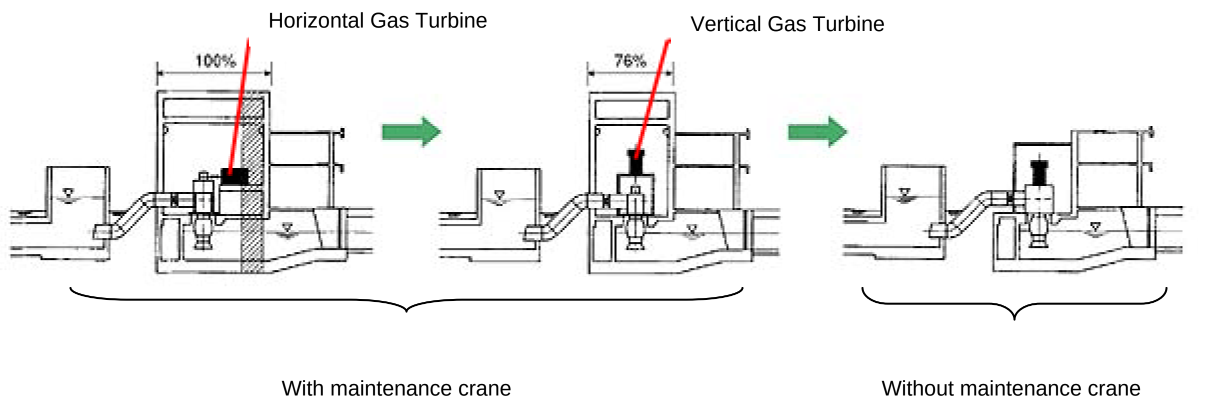

Figure 5. Space Savings for Vertical Gas Turbine Installation

In applying the ASE40V to the vertical pump application, the customer specified the following design criteria:

- A duty cycle of 30 minutes of operation per month and up to 72 hours of continuous duty
- Total operational time of 2000 hours based on 300 hours of operation per year
- An overhaul maintenance interval of 5 years
- Fast starting capability to reach full output power within one minute

The ASE40V gas turbine easily met these criteria due to its rugged construction, high cycle endurance, and unique fast starting capabilities. Other factors considered by the customer in applying the ASE40V to the vertical pump application were the torsional characteristics relative to the vertical pump design and blade containment of the compressor and turbine blades for the planned standby operation.

Torsional Analysis

Initially the customer had concerns with the critical speed for the gas generator and power turbine when coupled to their vertical pump system. The combined vertical gas turbine and pump system were analyzed to predict the resulting torsional natural frequencies and modal characteristics. The vertical system was modeled by lumping the mass/inertia and stiffnesses with varying degrees of freedom. The torsional analysis used two different modeling techniques that matched almost exactly for the first two modes and matched reasonably close for the subsequently higher modes. The study concluded that the vertical gas turbine engine was not likely to excite through any of the torsional values over the entire operating speed range.

Blade Containment

The customer had previously experienced compressor and turbine blade containment problems with another manufacturer’s gas turbine in a standby generator application. A request was made by the customer to analyze the need for a containment ring to protect against blade burst events. The concerns were quickly discounted since previous blade containment studies required by the Federal Aviation Administration had already been performed for the axial compressor, centrifugal impeller and turbine stages for the T-55 gas turbine. The results of the study demonstrated that there were no blade containment concerns in either military or commercial service.

Once the system analysis was completed, the customer proceeded with the design and construction of the vertical pump package as shown in Figure 6, with and without the enclosure.

Figure 6. Vertical Pump Package with and without Enclosure

Today there are seven ASE40V’s installed in vertical pump drive applications ranging from 1400 kW (1877 shaft horsepower) to 2400 kW (3218 shaft horsepower). Each gas turbine is cycled on a monthly basis for start testing and undergoes an annual borescope inspection. Due to the minimal accumulated operating and cycles, the maintenance costs are relatively low throughout the life of the engine. The ASE40V has performed successfully in the field as well as in production testing, resulting in an expressed interest in future sales by municipalities in Japan. With the recent relocation of the assembly and test facility, production acceptance testing methods for future ASE40Vs were re-evaluated.

Production Acceptance Testing Methods

The currently installed turbines were tested with an outdoor test apparatus due to limited test cell space at the original assembly and test facility. The outdoor configuration offered the benefits of a low capital investment that was appropriate for the annual sales projection. The disadvantages, however, were the limitations imposed by inclement weather, increased setup effort, and noise issues. Therefore, horizontal testing consistent with the ASE40 engine was considered to allow for year-round testing in the existing test cell. This eliminates the inclement weather and noise constraints.

To substantiate and perform the test of the vertical gas turbine in the horizontal orientation, the major differences between the two engines were re-examined. Three areas were highlighted to undergo a more detailed review;

The 1st area of review for the horizontal test was the oil flow from the power turbine sump. For the vertical configuration, changes were made to the power turbine sump to improve oil flow out of the sump during vertical operation. These changes did not adversely affect the operation of the sump in the horizontal position. This is due to the fact that lubrication oil is effectively scavenged from the bottom of the oil sump by the oil scavenge pump. Whether tested in horizontal or vertical orientations, the sump is drained from the same point and thus the position of the engine was determined to not be an issue.

The 2nd item to examine was a minor change to the housing of the output shaft, which incorporated a drain hole in the housing to drain oil from the No. 6 & 7 bearing area. With this modification the oil can not drain into the inlet housing module when tested horizontally. The hole was plugged from the outside of the housing to allow the oil to drain in a manner similar to the horizontal configuration.

The configuration of the accessory gearbox was the 3rd and final difference considered between the horizontal and vertical ASE40 configurations as applied to the horizontal test. Due to the configuration changes from a horizontal to a vertical accessory gearbox, the vertical accessory gearbox could not be run in the horizontal position for extended periods due to concerns of effective oil feed and scavenging of the bearings.

The need to operate the vertical accessory gearbox in the vertical position precluded acceptance testing of the ASE40V in the horizontal position. The proposed option was to use a slave horizontal accessory gearbox for testing in the horizontal position and to replace the horizontal gearbox with a vertical gearbox before shipping the engine to the customer. The installation of the vertical gearbox on the inlet housing requires significant care in aligning the two components and the tower shaft. There is no method other than a test to ensure the gearbox is functioning correctly. It was decided to operationally check the vertical accessory gearbox for oil leaks by conducting a two minute run at idle in the horizontal position and to conduct a post-test borescope inspection of the accessory gearbox.

Production and MRO Facilities

In 2005 Vericor Power Systems and Standard Aero Ltd of Winnipeg signed a contract for Standard Aero to carry out new production assembly and test as well as overhaul and repair support to Vericor products. To date almost 70 new production engines have been assembled and tested. Also, a number of repairs have been completed both on complete engine assemblies as well as component repairs. Though there has not yet been a requirement for the ASE40V engine to be completed in the facility the difficulty of the vertical setup and weather shall not be a factor in Winnipeg due to the elimination of the vertical test.

Conclusion

The application of the ASE40V gas turbine to the vertical pump drive proved to be a relatively simple endeavor. Only minor engine modifications were required to prevent fuel and oil accumulation in the vertical orientation. The structural integrity of engine components combined with the rugged construction of the ASE40V was more than adequate to support the weight of the engine for successful vertical operation. Coupling the engine to the vertical pump system was also straight forward due to the customer’s extensive experience in packaging the ASE40 engine in horizontal compressor drive and generator applications.

As the need for smaller installed footprints becomes more prevalent in the marketplace, the ASE40V will be an ideal candidate for other vertical power and mechanical drive applications. In particular, the oil and gas industry can benefit significantly from the proven vertical design. Not only is space conserved by the vertical turbine and gearbox, but there are even greater space savings that can be attained by routing the exhaust ductwork directly in the vertical orientation.

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