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Design, Development and Applications of Jet Engine Based 800-kW Gas Turbine

J. SINAI

J. ROZEWICZ

Bet-Shemesh Engines Ltd.,
Bet-Shemesh, Israel

This paper describes the design and test work of a development program of a 800-kW industrial gas turbine utilizing a jet engine gas generator. Design and subsequent manufacture of the power turbine assembly was predicated upon the use of aircraft engine components and technology. The gas turbine was initially intended as standby electric power source. It is planned to utilize the unit in continuous duty service. Solution of aerodynamic and mechanical design problems, and adaptation of control system are outlined. The results of prototype tests are also reported. Performance data correlated well with expected values. Several units have been installed up to date for standby utility service in industrial complexes, airport terminals and on ships. Operational experience with these engines is reviewed.

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1 INTRODUCTION

This paper describes the design and test work conducted during a program to develop a 800-kw gas turbine power plant designated as M2TL. The program had, as its objective, the development of a gas turbine, distinguished by high reliability, cheapness of manufacture, and ease of maintenance. With these points in mind, it was decided to utilize a gas generator of turbojet engine-Turbomeca Marbore 2. It is a nominal 400-kgf thrust engine and had logged several millions of hours in trainer aircraft. Its construction is very simple and reliable. The engine was manufactured in large quantities in France, the United States, and Israel, and considerable manufacturing and operational experience have been accumulated.

The development work included a design of a free power turbine and reduction gear, and modification of control and fuel system to permit operation on industrial fuels.

The program conducted at Bet-Shemesh Engines Ltd., a company partly owned by Turbomeca S.A. France, was intended to produce a practical unit mainly for standby generator sets. The utilization of the gas turbine for continuous duty generator sets and mechanical drives in places where inexpensive fuel is available, and for total energy systems, has been also considered.

The accent has been placed upon low installation cost of the unit and short development time. These requirements have dictated utilization in design, as far as possible, of engine components being manufactured in Turbomeca Company. It allows to reduce components tests and to limit preparation of special fabrication methods and tools. Some examples of this design conceptions are presented in this paper.

NOMENCLATURE

I = electric current, A

m = air mass flow, kg/sec

N = gas generator rotational speed, rpm

n = output shaft rotational speed, rpm

P_0 = ambient pressure, bar

P_2 = compressor discharge pressure, bar

T_0 = ambient temperature, deg K

T_3 = gas generator turbine inlet temperature, deg K

t = time, sec

W = power output, kw

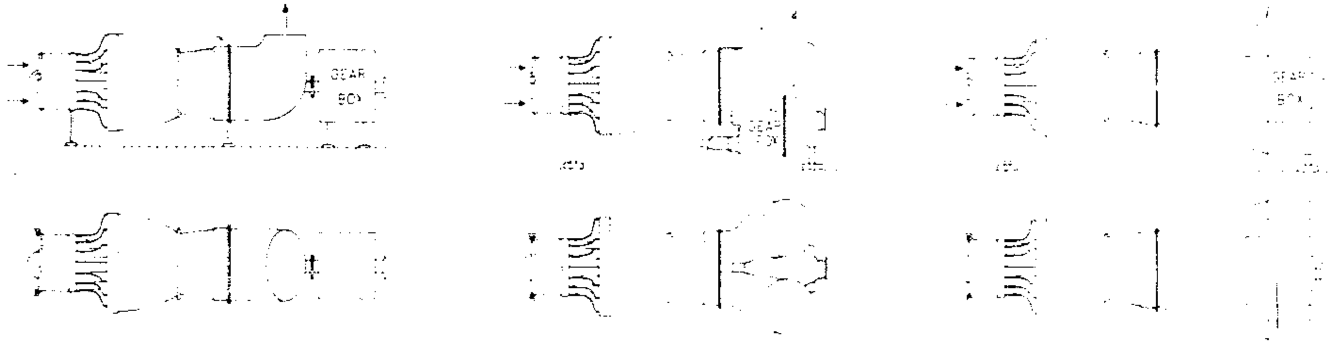
2 GENERAL DESIGN CONSIDERATIONS

The gas turbine power plant configuration was established as consisting of gas generator, free power turbine, and reduction gear.

As the use of existing gas generator was specified, the freedom of design point selection was limited. The estimation of the gas generator performance data was based upon a performance map of existing turbojet engine.

Table 1 Gas Generator Performance Data

	Base load	Peaking
Rotational speed, rpm	22,200	22,500
Compressor pressure ratio	3.8	3.9
Airflow rate, kg/sec	7.6	[illegible].0
Turbine inlet temperature, deg C	750	7[illegible]0
Turbine outlet temperature, deg C	610	650
Turbine outlet pressure, bar	1.70	1.75
Fuel rate, kg/ sec	0.122	0.1[illegible]



ALTERNATIVE A ALTERNATIVE B ALTERNATIVE C

Fig. 2 Alternative design solutions of engine rear part containing power turbine, exhaust pipe, and reduction gear

There were several types of blades which were considered as possible for adaptation. The selection was done by multi-variant design calculations, which involved quasi-three-dimensional flow analysis, based on radial equilibrium theory. The constant nozzle angle was assumed and zero exit swirl was specified as the design condition.

The selection process was conducted on a trial and error basis. Three design parameters of the power turbine had been considered as variable: mean diameter, blade height, and stage load. Utilization of a computer and examination of the change in the solution due to incremental changes in the foregoing design parameters produced adequate guidance in the selection of the blade shapes.

The design had been checked and subsequently corrected by estimation of nozzle and rotor losses.

According to calculated results, it was found that the final blade configuration should exhibit an exit swirl angle equal to zero at the mean radius and up to 2 deg at the tip and hub sections.

In the process of design calculations of the turbine stage, some uncertain assumptions were involved. For instance, an assessment of cascade performance and stage efficiency was based on the assumption of full similarity of flow conditions in designed, and in previously experimentally tested stages. An accuracy in the prediction of the performance of the gas generator while working with attached power turbine was also questionable. As the attached power turbine has a mutual influence on compressor characteristic, the location of the gas generator operating line on the compressor map may be disclosed only by test measurements.

As was mentioned in the foregoing, for reducing price and time of the power plant development the component tests were not carried out. However, in order to avoid possible consequences of inaccuracy in the assumption undertaken, additional design considerations and calculations have been carried out.

As a result, besides the originally designed configuration, assigned as alternative No. 1, two additional alternative design solutions of stage geometry were provided.

The difference of the alternative solutions consists in various setting angles of designed stator nozzles. In alternative No. 2, the stator nozzles setting angle, measured from the axial direction, was decreased by 1 deg-30 min. In alternative No. 3, the stator nozzle setting angle was increased by 1 deg-35 min. in comparison with the originally designed value. Consequently, the throat area of stator nozzles was changed by +4.5 and -4.2 percent, respectively.

It was decided to select an optimal alternative in the course of prototype tests. This procedure was chosen because of the convenience of manufacturing a monocast nozzle wheel by the investment casting method. By using this method, only a mold for one single vane is required. For the three versions designed, the wax patterns were prepared from vanes of the same mold and assembled in three different fixtures.

4 MECHANICAL STRUCTURE

The General Design of the Rear Part

The general conception was to use aircraft technology for the rotating parts, mainly the turbine and pinion shafts, while using heavier and less difficult to manufacture industrial design for other parts.

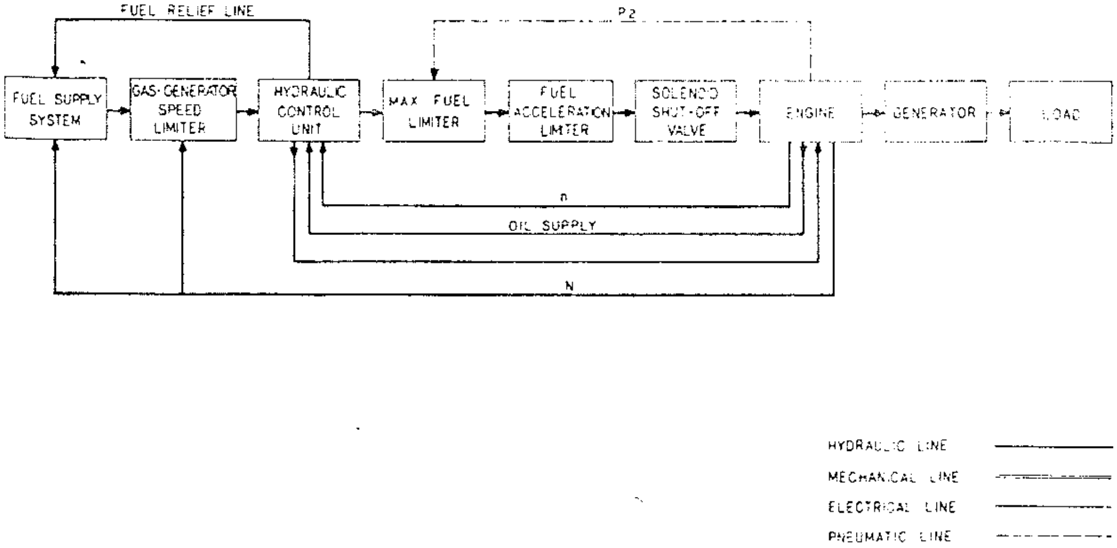


Fig. 3 Hydromechanical control system block diagram

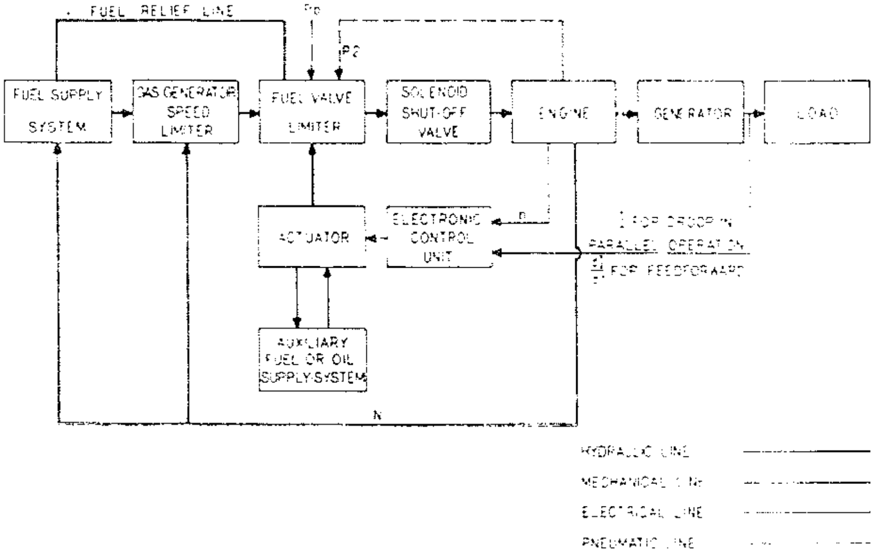


Fig. 4 Electronic control system block diagram

From the three possible configurations shown in Fig. 2, alternative B was chosen because of minimum requirements for new tools. Casting models for similar aluminum parts of helicopter engines were used for the M2TL cast iron gear casing. The main drawback of this configuration is the complicated form of the tailpipe which was hand manufactured.

A modification of the design to alternative C will be considered when a sufficient number of orders are received to warrant an increase in production.

Reduction Gear

Two versions of a reduction gear were built: one-stage reduction for 3000-rpm output shaft speed, and two-stage reduction for 1500- or 1800-rpm output shaft speeds. Both versions use helical gears, ball and roller bearings, dry-sump pressure lubrication, and cast iron casing. The first stage, high-speed gear and pinion were designed to withstand the wear mainly due to scoring. This was done by using aircraft technologies and materials, and minimizing relative specific sliding speed at the teeth impact point by special addendum modifications.

High speed shaft bearings are aircraft type, made of vacuum-melted materials and narrower tolerances, while lower speed bearings, gear casing, and second-stage shaft materials resemble

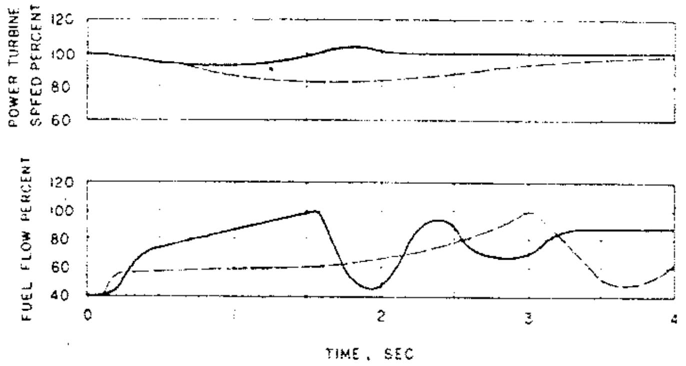


Fig. 5 Response of engine to sudden load from 50 to 700 kw, a) —— electronic governor, b) —— hydraulic governor

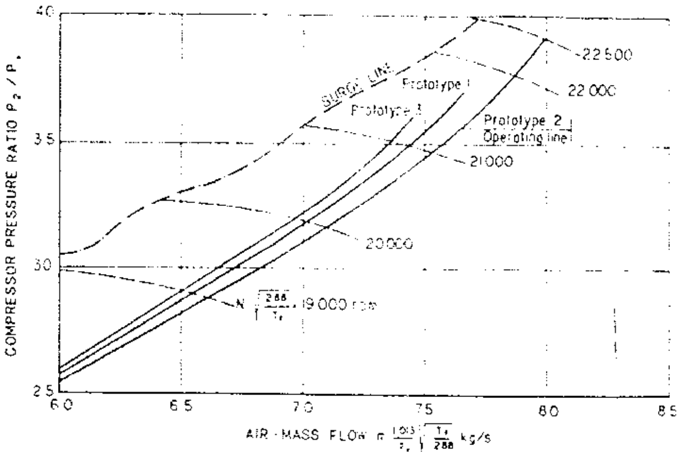


Fig. 6 Compressor chart

industrial design concepts.

5 CONTROL SYSTEM

It was decided to adopt an electronic fuel control system. Since the aircraft engines use a hydromechanical fuel control, development of the electronic control required extensive re-engineering and test running.

This control serves three principal functions:

1. Speed governing of the gas generator and the free turbine
2. Control of acceleration
3. Protective shutdown features.

Some electronic control systems were offered to match the M2TL turbines. However, all the electronic control manufacturers required a certain amount of data that could only be evaluated in engine tests. It was decided, therefore, to deliver the first sets with hydromechanical system and to accumulate the required data from these engines.

The hydromechanical system was an helicopter type isochronous control. The block diagram of the system is shown in Fig. 3. It was not suitable for operation in parallel (synchronizing) and had a relative low limit of maximum permissible gain because of stability consideration.

The electronic control system that was chosen afterward is made by Woodward Governor Co. of U.S.A. Fig. 4 shows the system block diagram. One of the control functions in this system is done mechanically, the acceleration being limited by the compressor discharge pressure rise. The system is suitable for both single (isochronous) and parallel operation. It is equipped with a droop matching device and is suitable for operation with load-sharing control. It has a special "feed forward" device that senses the load rise and the load current, and gives an early signal to the governor in order to minimize undershoot in the case of sudden loading. Satisfactory results have been achieved with this system. A typical plot of the recorded data is shown in Fig. 5.

The Woodward governor renders also the task of bringing the engine from low speed (end of start) to nominal speed by a suitable ramp generator.

Another system which is being developed at present is an electronic starting panel. This system will minimize the engine penalty for starting by using an appropriate sequence depending both on time delays and measured engine parameters.

6 TEST PROGRAM AND RESULTS

The basic prototype series consisted of three engines. While the gas generators of the engines were identical, the power turbine has been constructed in three alternatives, specified above in Section 3.

Testing was conducted in the Company test laboratory. The program test plan included:

1. Preliminary tests
2. Performance tests
3. Auxiliary systems tests
4. Qualification testing.

After confirming the engines feasibility in preliminary tests, each prototype was experimentally investigated in order to determine power, specific fuel consumption, and other performance characteristics.

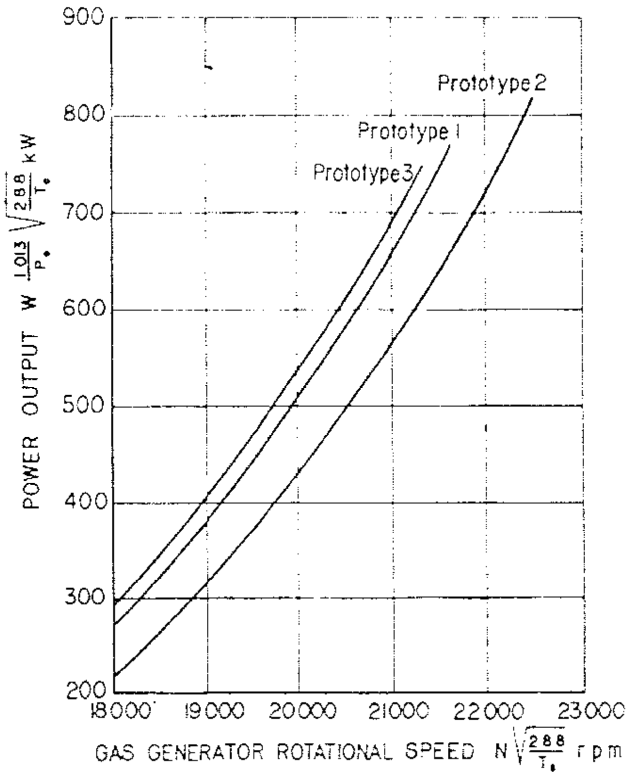


Fig. 7 Power output variations with gas generator speed

Two basic restrictions have been specified for tests conducted:

1. The maximum cycle temperature, i.e., gas generator turbine inlet temperature of 780 C
2. Maximum gas generator rotational speed of 22,600 rpm.

The external environment conditions varied during the performance tests, but measured and calculated parameters have been converted to standard atmospheric conditions and, in such form, are cited in the following. The output shaft rotational speed was maintained at 3000 ± 15 rpm.

Some significant results of performance tests are shown graphically in Figs. 6, 7, and 8.

Analysis of compressor operating lines which are plotted in Fig. 6 indicates that the working conditions of prototype No. 2 are very similar to that predicted in design calculations. The compressor operating lines of prototypes Nos. 1 and 3 are located on the compressor chart more closely to the surge line. Therefore, in these cases, at the given gas generator rotational speed, the compressor pressure ratios were higher, while the airflow rates were lower than desirable.

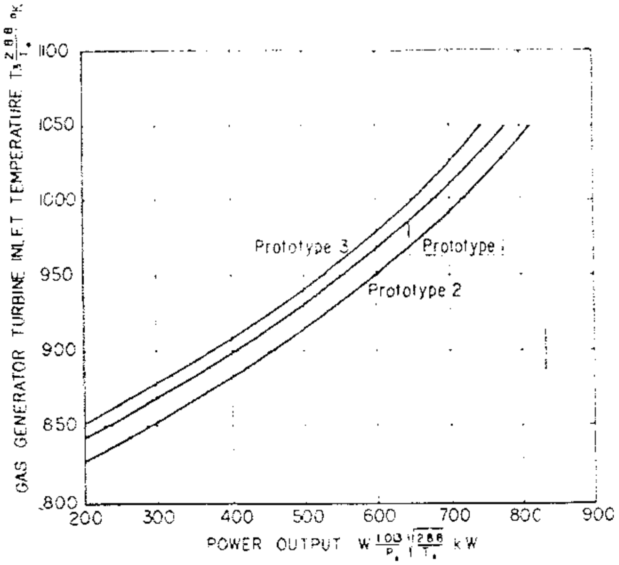


Fig. 8 Maximum cycle temperature variations with power output

However, the resulting power outputs were relatively higher than obtained in prototype No. 2 for a given rotational speed (Fig. 7), but were produced by higher maximum cycle temperature. Consequently, the maximum cycle temperatures corresponding to given rating were higher for prototypes Nos. 1 and 3 than for prototype No. 2. This is shown in Fig. 8.

The peaking load of each of three prototypes was limited by force of the maximum cycle temperature restriction. In Table 3 are shown the performance data of prototype engines while maximum cycle temperature reached 780 C.

The results of performance tests indicated that the design alternative represented by prototype No. 2 completely satisfies the design objectives. The assumed base load and peaking load have been gained, and specific fuel consumption was on the estimated level.

Prototypes Nos. 1 and 3 did not reach the peak rating specified in the design aim.

Therefore, it was decided to establish the prototype engine No. 2 as the basic prototype engine, and only this one was subjected to further testing outlined by the program test plan.

The tests of engine auxiliary systems examined performance of fuel system, control system, lubricating system, and protection devices. The tests demonstrated that engine auxiliary systems were constructed properly and operate adequately.

The final qualification test consisted of long duration tests carried out on a dynamometer test stand, followed by experimental runs outside the test laboratory with electrical generator

Table 5 Peaking Load and Performance of Prototype Engines

Prototype number	1	2	3
Peaking load, kW	780	820	750
Gas generator rotational speed, rpm	21,700	22,500	21,300
Airflow rate, kg/sec	7.65	8.00	7.45
Compressor pressure ratio	3.7	3.9	3.6
Specific fuel consumption, g/kwh	570	565	580

attached.

The prototype No. 2 accumulated about 120 hr of test runs. After these tests, the new parts installed in the prototype were inspected. The parts appeared to be in good condition and no damage has been revealed.

7 APPLICATIONS

Since the prototype test performed in mid-1971, several M2TL gas turbine power plant have become operative.

In the first instance, the units have been installed as standby electric power sources of industrial plants. The complete unit includes the M2TL gas turbine, an electric generator with voltage regulation system, and auxiliary accessories like fuel tank, oil tank with oil cooler, starter batteries, and a control panel. The unit is mounted on a common frame base and housed inside an acoustically treated enclosure.

Fig. 9 shows the standby electric power unit installed in an airport terminal power plant.

As standby units, they did not accumulate many working hours. The greatest experience belongs to a power plant installed in a tire factory, which logged in a two-year period some 200 working hours and some 250 starts.

The operational experience has been satisfactory to date, with relatively few minor problems which arose in the first months of operation. The modifications that were made as a result of this experience are:

1 Altering of the starting sequence
2 Switching to electronic control system in the cases where sudden load is applied
3 Separation of the pressure side of the gas generator and power turbine assembly lubrication systems.

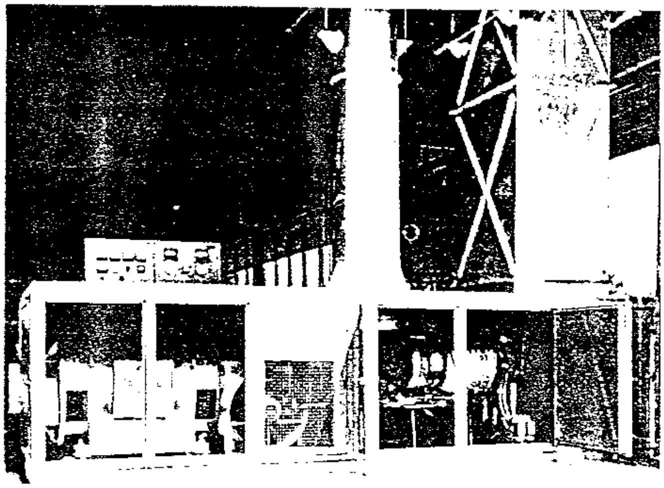


Fig. 9 M2TL electric power unit installed in an airport terminal

In March 1973, an installation of the M2TL electric power unit was made in a Dutch shipyard on a super-tanker vessel. For this application, the engine underwent a special anti-corrosion treatment. The unit serves as a standby ship board auxiliary power source. It is fully automated and is started automatically when a break in energy supplies from other sources occurs. Its operational capabilities were successfully tested by the vessel tests on the North Sea, and further in practical operation on the Red Sea. Since starting to operate through August 1973, the unit performed about 80 starts and accumulated some 25 hr of practical service. The experience has been very satisfactory to date.

Some orders have been obtained for continuous duty applications. It is planned to utilize the units in regions where inexpensive natural gas fuel is available. The construction of engines with fuel system adapted to the use of natural gas is actually in progress.

The applications study carried out indicated that utilization of the M2TL gas turbine in total energy system will give an opportunity to achieve overall plant thermal efficiency in the range of 70 to 75 percent.

8 CONCLUSIONS

The following conclusions are drawn from design analysis, experimental tests, and operational experience:

1 The design and construction of three alternative prototypes of gas turbine allowed the design aims to be achieved in the first attempt and permitted a reduction in the engine development period.

2 The utilization of a reliable gas generator and proven aircraft engine components resulted in the prototypes and first sets ordered being erected with particular ease.

3 The hydromechanical control system was adequate for some applications. The experience logged with this system permitted the testing and incorporation of advanced electronic systems into engines requiring this level of sophistication.

4 In standby applications, this power plant is ideally suited, due to its excellent starting characteristics, reliability, and simple maintenance.

5 There is no experience up to date in continuous duty operation of the power plant. The specific fuel consumption in the range of 570 g/kwh indicates, however, that the unit may be recommended for continuous duty service in places where expenses for fuel are of secondary consideration, while the investment costs are of primary importance, or in total energy installations.