

Stepped Piston Engines for Multi-Fuel UAV Application

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SYNOPSIS

This paper presents design and development data for the SPV580 Unmanned Air Vehicle (UAV) engine. The project was funded by the British Ministry of Defence to meet future need for low mass power plants for advanced UAVs. Development has investigated gasoline and heavy fuelling, and data is presented on the achievements to date, together with predictive data if more advanced fuel system technology is applied. Summary data from a further study to provide higher power output from low mass stepped piston engines is also presented.

1. INTRODUCTION

Bernard Hooper formerly Chief Engineer of Norton Villiers Ltd and designer of the highly successful Norton Commando motorcycle, and Starmaker/Stormer two-cycle engines established Bernard Hooper Engineering Ltd in 1977. Work commenced in order to forward development of the stepped piston engine, building on earlier achievements [1], together with parallel project work on two and four-cycle engines for Automotive, Marine, Industrial and Defence sectors. UAV Engines have been developed using stepped piston pump charging and conventional two-cycle crankcase scavenging. BHE has also provided in depth computational analysis of existing proprietary engines often identifying areas for performance and durability improvement and has supplied improved engines to meet these targets.

Progressive design and development work has enabled refinement to a point where UAV requirements for low mass engines could be seriously considered. This resulted in MoD contract work to design and develop an advanced 30-35kW UAV engine, overcoming conventional engine drawbacks. Within an engine mass of 17.45kg the original SPV580 engine has met all the design criteria. Subsequent contract work, in response to NATO objectives, has investigated heavy fuel operation. This paper provides a comparison of the SPV580 engine with other typical UAV engines. Some of BHE's heavy fuelling development has been covered in more detail in a previously published paper [2], however summary data is presented, together with recent predictive analysis of more advanced fuelling, and computational modelling considering possible higher power requirements.

2. STEPPED PISTON SPX ENGINE OPERATING PRINCIPLE

The stepped piston SPX operating principle is shown schematically for reference in Fig 1.

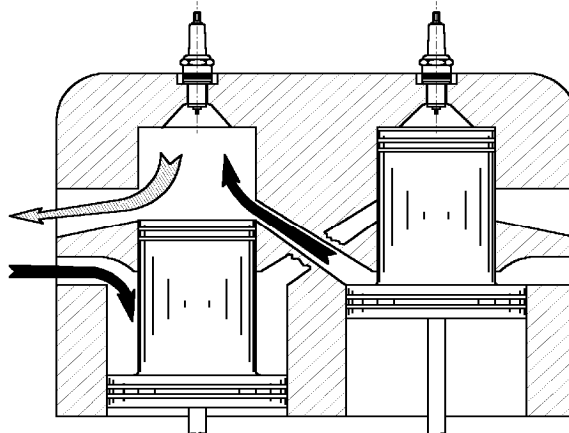


Fig.1. SPX Operating Principle (Schematic)

The SPV580 is a 90° V4 cylinder engine and operates with two banks of paired cylinders. Air and fuel mixture (or air only for direct injection) is drawn into the pumping annulus through a reed valve. As the piston ascends the charge is transferred through a crossover system to the smaller diameter or working cylinder. The engine then operates as a loop scavenged engine, except that the crankcase isolation afforded by the stepped piston enables fundamental durability and operational advantages.

3. STEPPED PISTON ENGINE DESIGN PHILOSOPHY

The use of stepped pistons for charge transfer and combustion allows the key advantages of two and four-cycle engines to be combined and elimination of disadvantages inherent in each of these engine types. As in the case for four-cycle engines, the charging and lubrication processes are physically separate in the stepped piston design. This eliminates a major source of problems that is common in crankcase scavenged two-cycle engines. Isolation of the fresh charge from the crankcase is made possible by the provision of normal four-cycle engine compression and oil control rings on the larger diameter part of the piston (see Fig.1.). The crankcase, freed from any gas exchange functions, is well lubricated; the working processes being sealed above the piston.

Isolation of the crankcase also permits a full pressure lubrication system to be used, as in four-cycle units. This simplifies fuelling needs with operation on neat fuels, avoiding the battlefield supply problems, uncertainty and risk of error inherent in the oil and fuel mixture required for conventional two-cycle UAV engines. Furthermore the inherent piston cooling characteristics of the stepped piston design offer a major durability advantage over conventional two-cycle engines, allowing much leaner fuel delivery than can be sustained with crankcase scavenging. Piston overheating and consequent seizure normally occurs with very lean air fuel mixture operation in crankcase scavenged engines.

The smooth output torque, provided by a power stroke from each cylinder for every revolution, retains an advantageous two-cycle characteristic. A particularly smooth arrangement, which is also very compact, is provided in a 90° V-4 layout. Having excellent balance, and with evenly spaced firing intervals, this gives smooth torque characteristics, which cannot be achieved in a four-cycle engine with less than eight cylinders.

The SPX design involved changes to the established layout of the transfer ports to suit the engine. The port layout adopted is unsuited to conventional units but, in SPX engines, it concentrates the scavenge flow at the wall of the cylinder opposite the exhaust port. This compares with more evenly dispersed scavenge flows common in conventional engines. Scavenge flow within the SPX cylinder provides, in effect, a form of stratified charging and explains improvements in fuel economy obtained with such a simple layout. This enables stepped piston engines to compete with four-cycle engines in terms of fuel economy, especially under cruise conditions. Multi-cylinder gasoline stepped piston engines now achieve specific power of 61kW/Litre, and are comparable with the high power achievable with two-cycle engines ported for maximum power at similar engine speeds of 5000-6000 RPM. Operational size and weight factors lie between two and four-cycle engines. SPX multi-cylinder engines, however, tend to be closer to two-cycle units in respect of performance and mass.

3.1 STEPPED PISTON ENGINE DURABILITY AND OPERATIONAL ADVANTAGES

- Conventional 4 cycle wet sump lubrication
- No valve gear
- Low thermal loading of the piston
- High durability with low exhaust emissions
- Compact low mass design
- Extended oil change periods (oil does not degrade)

4. SPV580 ENGINE DESIGN

4.1 PRINCIPLE UAV ENGINE DESIGN CONTRACT OBJECTIVES

The following customer specified design objectives were set as key targets at the start of the design phase: -

- Low engine mass
- Reliability and Life
- Minimum Vibration and Torque fluctuation
- Minimum Noise & Heat Signature
- Good Fuel Consumption
- 30kW Engine Power at a maximum of 6000 RPM using simple stub exhausts
- Operating attitudes to accommodate bank, climb and dive angles up to $\pm 35^\circ$

4.2 ENGINE CONFIGURATIONS

Computational engine modelling and CAD has been used to optimise the engine design. BHE have developed specific models to optimise cylinder porting supported by techniques for simulation of pressure-time history in upper and lower cylinder, air box and inlet tract, charging and trapping efficiencies, main and auxiliary transfer and exhaust port mass flow rates, and reed valve flow area-time history. The software was also used to great effect in the study of exhaust system configurations. BHE also developed software to study engine loading and bearing life. Finite Element Analysis software was also used for key component analysis.

4.2.1 SPV580LC LIQUID COOLED ENGINE

An outline of the SPV580LC unit is shown in Fig 2. Cooling is provided by limited direct-flow water feeds to each cylinder.

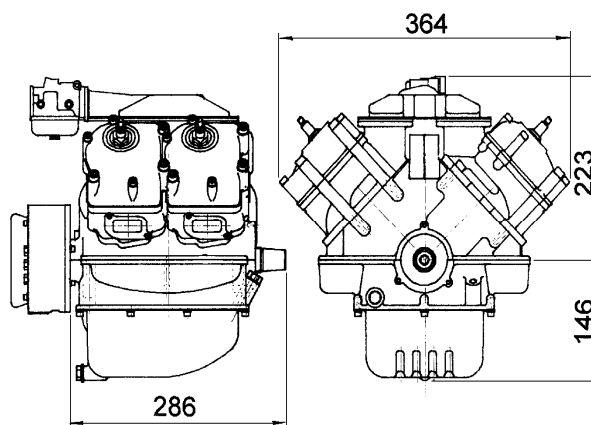


Fig.2. SPV580LC Liquid Cooled Engine Outline

4.2.2 SPV580AC AIR COOLED ENGINE

An outline of the SPV580AC engine is displayed in Fig.3. Cooling aspects were designed using the technology established by Mackerle [3], and experience of many small air-cooled two-cycle engines. A Centrifugal fan system was developed to allow dynamometer test evaluation. Except for their cylinders both versions share the same component inventory.

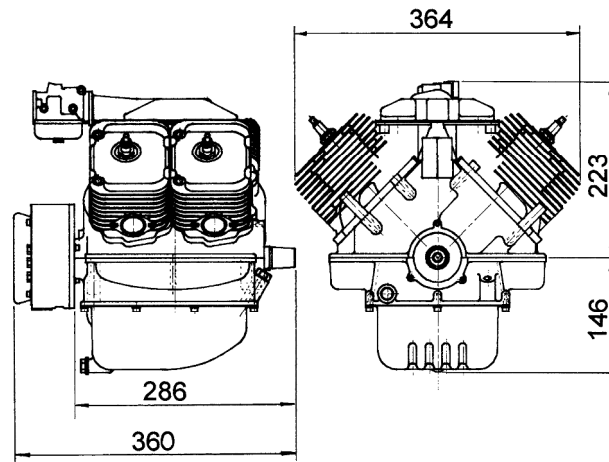


Fig.3. SPV580AC Air Cooled Engine Outline

A 900W FR-Hitemp generator, shown on the left in Fig 2 and 3, provides onboard electrical power.

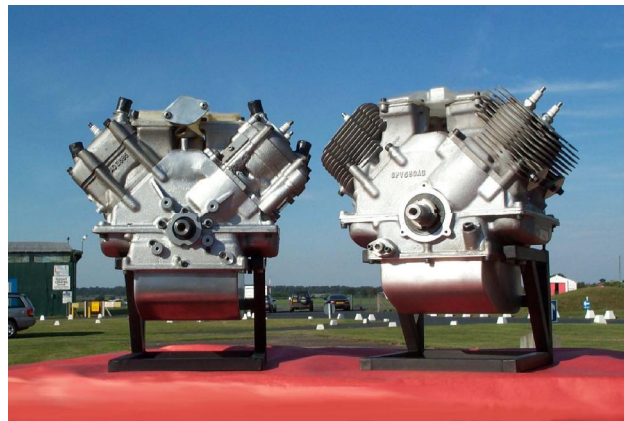


Fig.4. SPV580 Liquid and Air-Cooled Engines

4.3 TORQUE FLUCTUATION CHARACTERISTICS

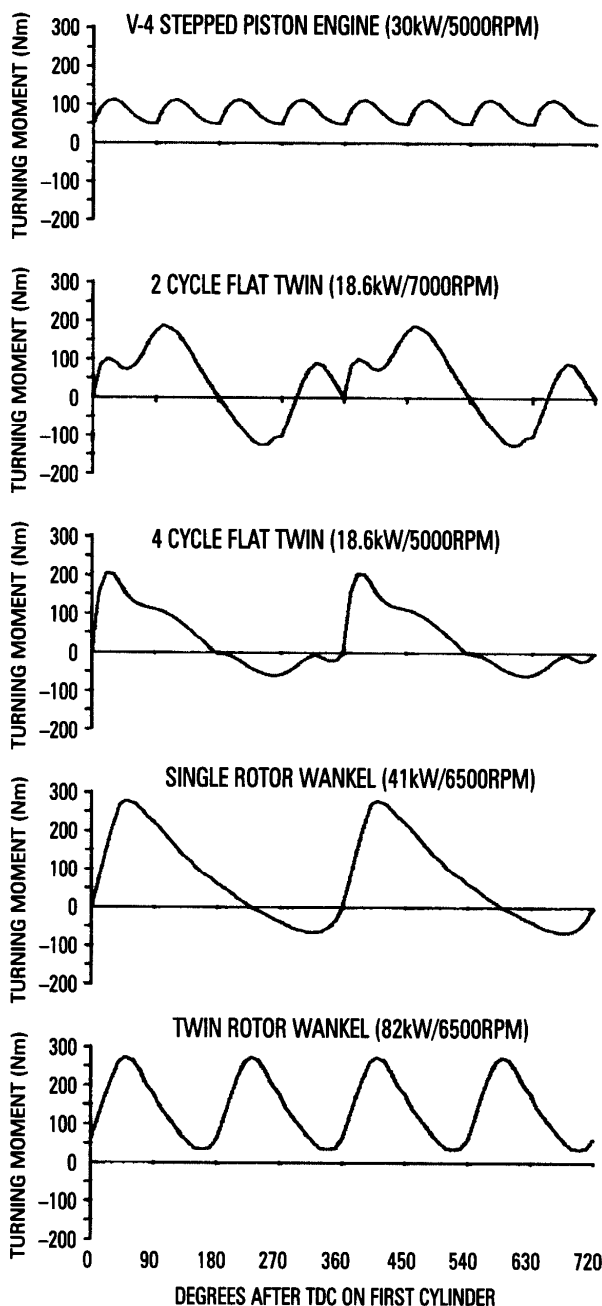
Two-cycle 90° V-4 engines, with each cylinder firing once per revolution give extremely smooth output torque characteristics similar to V-8 four-cycle engines. This feature is particularly valuable where minimal vibration and torque fluctuation must be achieved.

Fig.5. displays turning moment diagrams for the SPV580, typical flat twin cylinder examples of two and four-cycle power plants and twin and single rotor Wankel engines. Plotted to the same scale, these diagrams demonstrate the smoothness of the SPV580 engine. The horizontal axis extends over two complete revolutions to allow one complete four-stroke cycle to be included. These engines are not of equal power and a factor, which is independent of power, is therefore useful. The ratio of Peak-to-Peak torque to mean torque provides such a factor and is recorded in Table.1, enabling comparison of the fundamental characteristics of each type of engine.

During the period shown in Fig 5 each cylinder of the SPV580 unit has two firing strokes, resulting in eight power pulses during the two revolutions. The major advantage of eliminating all reversals of torque is thereby provided, the diagram being positive at all times. Each power pulse is comparatively small.

In the two-cycle flat twin the cylinders fire simultaneously, giving only two power pulses during the period shown. The power pulses are much larger than in the SPV580 and, being added together are the cause of large fluctuations in the turning moment diagram. In the case of the four-cycle flat twin, the cylinders fire alternately, but only once every two revolutions. Peak pressures within the four-cycle engine are much higher than in a two-cycle unit, resulting in stronger but less frequent power pulses. This makes the torque characteristics of the engine similar to the previous example.

Single rotor Wankel engines fire once per revolution, thus producing turning moment diagrams generally similar to the flat twin four-cycle. Operation on the four-stroke cycle entails negative periods or reversals in the turning moment diagram and torsional vibration levels that are still significant but lower than either of the flat twin engines. The single rotor Wankel engine shown in Fig 5 is based on an NSU unit [4], and is indicative of any single rotor engine. The twin rotor unit demonstrates the advantage of adopting multiple rotors.



Engine Type	Torque (Nm)		Pk-Pk /mean Factor
	Mean	Pk-Pk	
SPV580	80.6	64.4	0.80
2 cycle flat twin	25.4	314.7	12.39
4 cycle flat twin	35.6	263.7	7.41
Wankel (1 Rotor)	71.2	344.4	4.84
Wankel (2 Rotor)	142.4	176.0	1.24

Table.1.Torsional Vibration Comparison

Fig.5. Turning Moment Diagrams

4.4 MAINTENANCE & TIME BETWEEN OVERHAUL

Stepped piston engines eliminate most of the maintenance operations required with conventional two and four-cycle engines. Operating conditions in the crankcase of stepped piston engines are very similar to those in a four-cycle unit. The copious supply of oil to the working parts minimises wear. However, blow-by gases, to which the bearings and the oil are usually exposed, are isolated above the piston step. Bearing corrosion problems, well known in two-cycle engines, are therefore avoided.

In addition to these more obvious points, analysis of oil, taken from an Automotive stepped piston engine after 400 hours of use, revealed that the lubricant was still within the specification for new oil. Normal degradation of the additives had not occurred. The explanation is that in a four-cycle engine all of the oil passes at some time into the high temperature region adjacent to the piston compression rings and is then returned to the crankcase. Therefore in a four-cycle engine all of the oil is exposed periodically to temperatures well in excess of the degrading point of the additive pack. This causes the qualities of the oil to decline throughout the period between oil changes. In stepped piston engines, however, this hot zone is lubricated by a simply metered small quantity of oil, on a total-loss basis. These points suggest that normal topping-up procedures are sufficient and that four-cycle type oil changes can be largely eliminated.

5. PERFORMANCE DEVELOPMENT

Development testing was carried out in parallel with computational gas dynamic modelling, including analysis of the pressure-time history, to achieve target power and fuel economy goals with the most simple low mass exhaust system. A separate system for each cylinder achieved maximum power of 35.4kW at 5250 RPM and specific fuel consumption (SFC) of 304g/kWh (see System Ref ETZ in Table.2. and Fig.6.). This system also offers a very low noise level and provides a reference against which alternative systems can be assessed. Development work resulting from computational modelling on alternatives, such as the QUBy and a range of more compact systems, culminated in a more compact JL18 system. The use of an attenuating muffler at the system outlet further reduces cruise SFC. Table 2 shows the results achieved with the best exhaust systems that have so far been developed for the SPV580 engine.

Exhaust System Ref.	Power (kW)	Engine Speed (RPM)	SFC (g/kWh)	
			WOT	Cruise
ETZ	35.4	5250	304	286
QUBy	32.0	5000	359	
JL18	32.5	5250	359	
2-1Stub	30.9	5000	372	334

Table.2. Full and cruise load performance

The cruise loading in Table 2 is typically 65% of full power levels. Full load performance of the ETZ, JL18 and 2-1 systems is compared in Fig 6. The engine exhaust system was finalised into two optional systems; the simple 32.5kW 2 into 1 pipe and chamber JL18 system and the lighter 30.9kW 2-1 stub pipe system. The weight of these finalised exhaust systems are 1154g and 508g respectively. Two systems are required per engine.

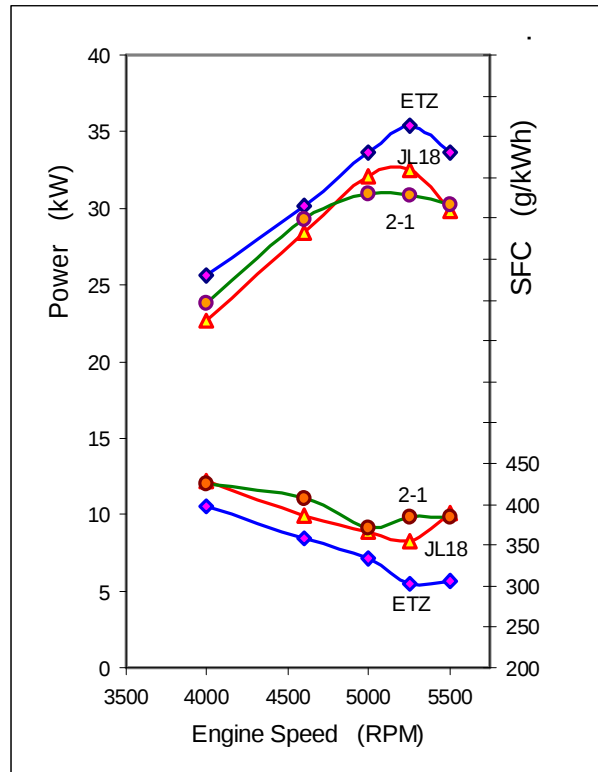


Fig.6. SPV580 performance with various exhaust systems - 95RON Gasoline (CD carburetter)

5.1 NOISE & HEAT SIGNATURE

Naturally a V-4 cylinder layout spreads heat sources, since each cylinder is a comparatively small source and they are spaced apart. Thus the heat intensity is reduced compared with flat twin or in-line types of engine of the same power rating. Four-cycle and Wankel engine exhaust gas temperatures are considerably higher than those produced by stepped piston and two-cycle engines. Four-cycle engines typically emit gas in the 700-800C range whilst Wankel engines are around 1000C. The SPV580 engine exhaust gas temperature is considerably lower in the 550–650C range.

The maximum noise level recorded at full power with the simple unattenuated 2 into 1 stub pipe system was 125.3dBA. The noise level with more advanced exhaust systems was typically of the order of 106.5dBA at full power, reducing to 103.8dBA at the nominal 65% cruise load condition. All measurements were recorded inside the test laboratory at positions 1 metre from the engine. Although impractical for many pre-existing aircraft, BHE has demonstrated the benefits of applying more advanced exhaust systems where allowance is made [5] for their installation. This work was demonstrated during BHE supply of engines for the QinetiQ Observer UAV, giving significant reduction in fuel consumption and greatly improved UAV stealth characteristics.

5.2 OIL CONSUMPTION

The engine of course operates on neat 95 RON unleaded gasoline or heavy fuel without the need for oil pre-mix. In comparison with conventional two-cycle engines, our stepped piston engines have so far achieved oil consumption of 0.5% (or 200:1) expressed as an equivalent ratio to the neat fuel consumed. This was recorded during independent 200 hour full load endurance testing and has been further demonstrated during more recent motorcycle engine development work.

6. MULTI-FUEL DEVELOPMENT

6.1 GASOLINE ENGINE

None of the SFC figures recorded in this paper relate to systems that take advantage of the inherent stratified charge porting, already designed into the SPV580 engine. This porting system has proved effective on an Automotive Stepped Piston engine of 994cm³, providing exceptional improvements in fuel economy, achieving levels down to 261g/kWh. Despite some work using semi-direct or transfer port injection of gasoline, most of the SPV580 engine development has used carburettor based fuelling systems. Using the simple stub type exhaust systems described above minimum SFC levels as low as 318g/kWh have been achieved. If more advanced low noise emission exhaust systems can be considered levels below 300g/kWh have been recorded using CD type carburettor technology. Use of direct injection would further secure these low SFC levels and would of course allow easier altitude compensation control. Furthermore due to the inherent ability to achieve high charging and scavenging efficiencies, high altitude operational benefits over conventional naturally aspirated engines [6][7] should be apparent with the stepped piston engine design.

6.2 HEAVY FUEL ENGINE

The SPV580 engine has been the subject of research work into the feasibility of operation on heavy fuels, notably kerosene JET A-1. Work has so far concentrated on semi-direct electro-magnetic injection methods with good power levels being achieved. Summary data for the engine is presented in Table.3.

The data presented is extracted from a more detailed study [2] however power within 5-10% of gasoline levels have so far been achieved. Further fuel system development is expected to yield lower SFC results and predictive work on this aspect is presented in section 7.1 below.

6.3 SUMMARY PERFORMANCE TO DATE

Engine	SPV580LC
Bore x Stroke	62mm x 48mm
Cylinders	4 (90° V-4)
Swept Volume	580cm ³
Dimensions (LxWxH) inc generator	360x364x369
Power 95RON Gasoline (Stub exhaust) Min Cruise SFC	30.9kW/5000RPM 318g/kWh
Power 95RON Gasoline (Advanced exhaust) Min Cruise SFC	35.4kW/5250RPM 286g/kWh
Power Heavy Fuel (Kerosene JET A-1) Min Cruise SFC (*) Achievable SFC (prediction)	30.5kW/5250RPM 437g/kWh (*) 360 g/kWh
Cooling System	Liquid (air option)
Mass	17.45kg (17.22kg)

(*) – achieved to date

Table.3. Summary Gasoline and Heavy Fuel performance – SPV580LC

7. STUDIES FOR FURTHER PERFORMANCE IMPROVEMENTS

7.1 ADVANCED HEAVY FUEL ENGINE

A further very recent study to assess the expected benefits of adopting a more advanced heavy fuel system, building on BHE's previous heavy fuel development work [2] as reported above, has also been made. 95RON Gasoline data shown in Fig 7 and 8 is reproduced from results achieved with simple carburettor technology. However lower gasoline SFC should be achievable via use of direct injection. This approach could achieve levels as low as 270g/kWh similar to those observed on our larger 994cm³ research engine. A minimum JET A-1 SFC of 360g/kWh is predicted in Fig 9.

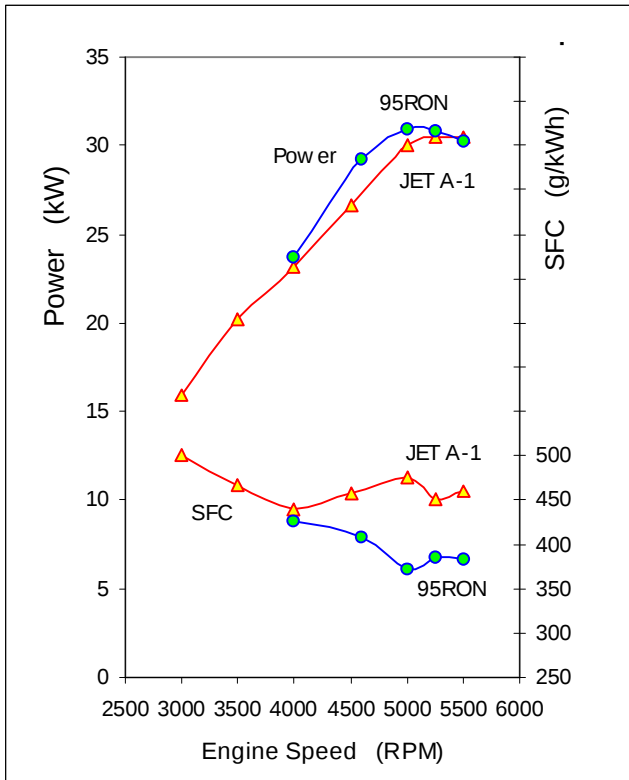


Fig 7. Expected JET A-1 full load results using more advanced fuel system technology

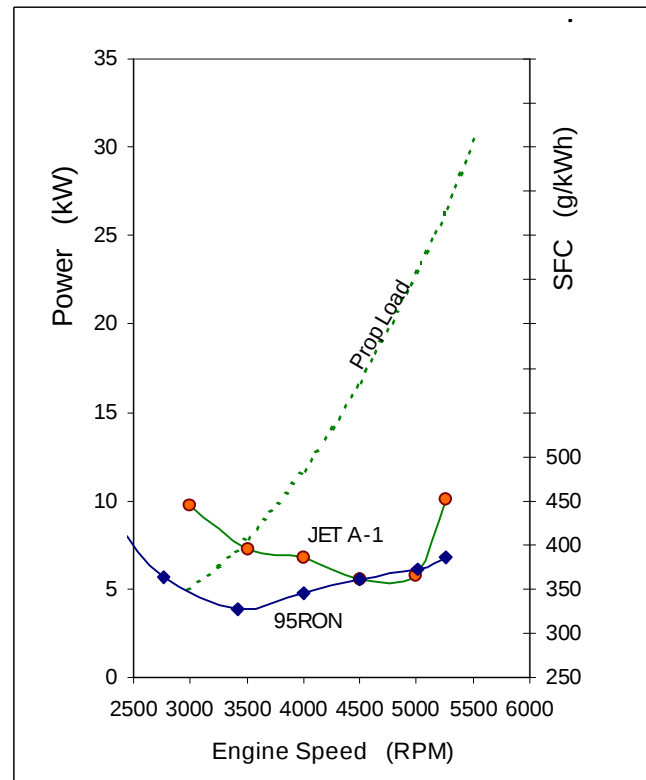


Fig 8. Predicted propeller load data using more advanced JET A-1 fuelling system

7.2 HIGHER SPEED SPV580HS ENGINE

In response to needs for very low mass propulsion systems exceeding the high power:weight ratio already achieved by the existing SPV580LC engine, a study was initiated by BHE to consider a revised SPV580 offering higher maximum power speed up to 6500 RPM. This resulted in the SPV580HS engine. The predicted full load performance for the high speed SPV580HS engine is presented in Fig 9. Redesign of the cylinder porting has been considered to allow higher maximum power/speed to be achieved. Our initial analysis shows a maximum power of 41.4kW. Maximum torque of 64.7Nm is computed at 6000 RPM.

The basic engine mass in Table 4 includes allowances for ignition system and carburettor. More advanced fuel systems will increase these figures. The ultra low mass version of the engine is based on a study employing magnesium castings for crankcase and cooling jacket components. Ultimate specific fuel consumption will depend largely on the final fuelling and exhaust systems selected. We would however expect specific fuel consumption similar to the levels achieved by the SPV580 engine with a gasoline minimum of 300-325g/kWh or 360g/kWh with JET A-1 fuelling using a simple

exhaust system. External dimensions for the engine are expected to be unchanged from the SPV580LC engine outline shown in Fig 2.

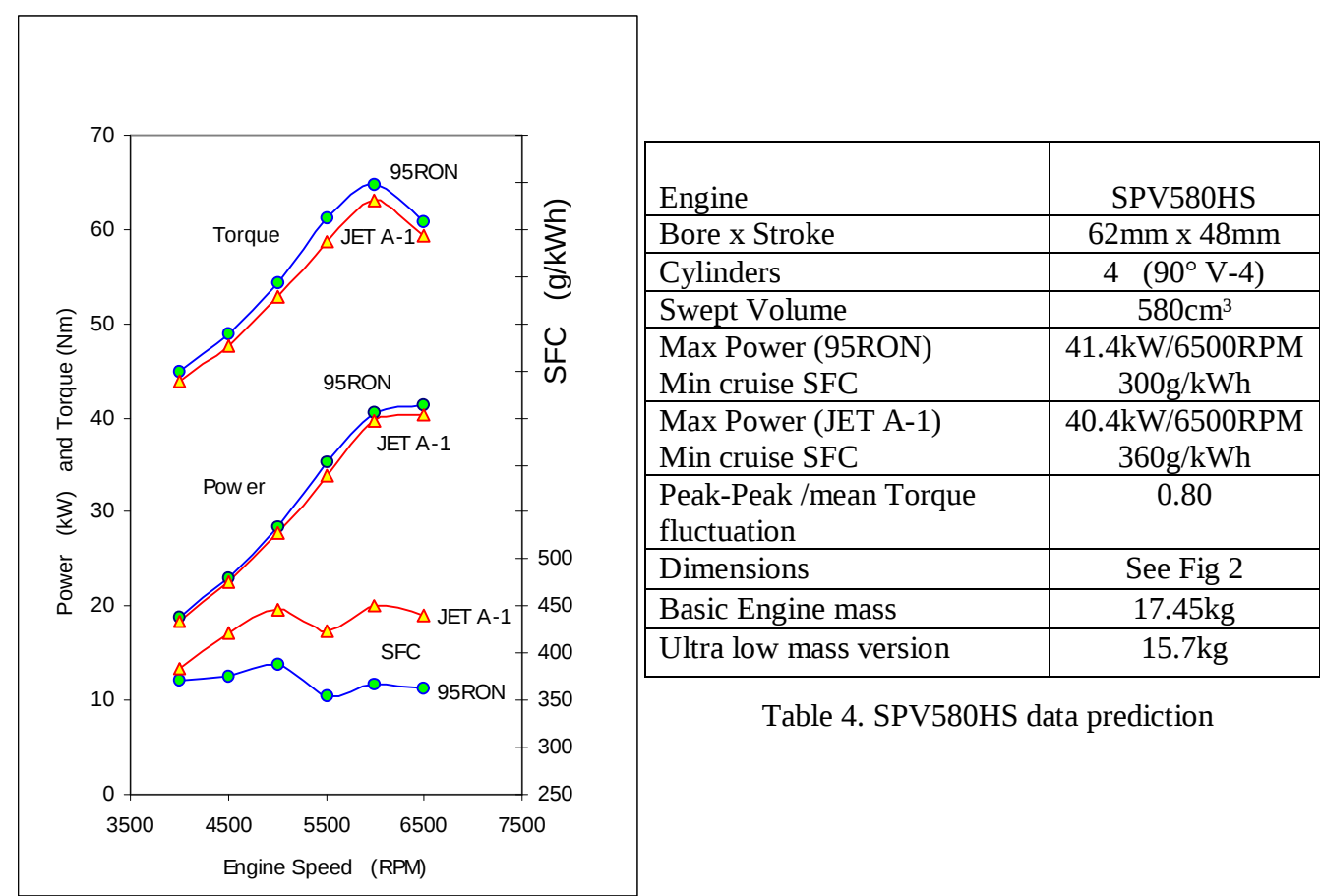


Fig 9. SPV580HS Engine performance prediction (95RON Gasoline or JET A-1 fuel)

8. CONCLUSIONS

The design and development of the SPV580 engine has met or surpassed the specified goals of low mass, high reliability, low vibration and torque fluctuation, good fuel consumption and power density. The feasibility of heavy fuel (kerosene JET A-1) operation has also been demonstrated, achieving power output within 5-10% of gasoline levels. Further kerosene fuel consumption benefits could be realised with more advanced fuelling methods. The higher maximum power speed SPV580HS engine suggests a gasoline power output of 41.4kW (or 40.4kW using JET A-1) at 6500RPM could be achievable.

9. ACKNOWLEDGEMENTS

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10. REFERENCES

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