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SPR Satellite Propulsion Research Ltd

Proposal for a SMART award to support the development of a microwave engine for satellite propulsion

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SIGNED. R.J. Shawyer

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DIRECTOR

Proposal for the development of a microwave engine for satellite propulsion

1. The Project

This project is the first stage of the development of a spacecraft engine employing a new propulsion technology which does not require reaction mass. The feasibility of this technology has been demonstrated, both theoretically and experimentally by the successful completion of the SMART feasibility study ref. 931.

The next stage is the design and development of a Demonstration Model (DM) engine. This will be tested on a dynamic test rig, to demonstrate continuous thrust and the conversion of thrust into kinetic energy.

The experimental thruster, tested during the feasibility study, clearly demonstrated the principles of operation and confirmed the theoretical performance predictions. However, thermal constraints limited the test runs to less than 50 seconds, the commercial magnetron used gave a pulsed thrust output, and thrust was measured on a series of static balance rigs. The performance of the experimental thruster was also limited by the relatively low Q operation that could be achieved.

Thus although a detailed review of the technical results confirmed the validity of the concept, further large-scale support of the work will need a more convincing demonstration. The purpose of the DM engine is to provide a clear visual demonstration of operation, as well as being the means of carrying out a detailed development programme.

The DM engine will be tested on either a rotary or a linear dynamic test rig. A rotary test rig would consist of a turntable mounted on an air bearing. The torque generated by the engine would enable rotary acceleration to be demonstrated and measured. The DM engine would incorporate a water-cooled magnetron and radiator together with a continuous high voltage power supply. The resulting continuous thrust would enable rotation to build up and provide clear visual proof of operation. By mounting the engine in three 90° configurations, forward reverse and zero torque operation will be demonstrated.

A development programme will also be carried out, by designing the resonant chamber to incorporate a number of different sections. These will allow performance measurements to be made for different design configurations and will enable higher Q operation to be progressively developed. Theoretical work has indicated that an increase in output thrust of almost ten times that obtained with the experimental thruster should be available.

The project will also enable further work to be directed towards obtaining the funding necessary for an Engineering Model (EM) engine. This would be a fully representative spacecraft engine and is a recognised critical step in the development of any new space technology. An EM programme would require a minimum funding of £1.5 million and this DM project is viewed as essential to obtain the necessary support.

2. Objectives

2.1. Design of a DM engine

The engine will be designed for an optimum power rating consistent with the maximum number of potential mission applications. The design will be for continuous operation and will incorporate interchangeable sections enabling the performance in different configurations to be measured.

2.2 Design of a dynamic test rig

A test rig will be designed that will enable the DM engine to be demonstrated dynamically. A rotary or a linear design will allow thrust to be converted into kinetic energy and the resulting acceleration to be measured.

2.3 Manufacture of a DM engine

The DM engine will be manufactured using precision machined aluminium components for the thruster sections. Industrial microwave components will be procured together with the necessary thermal subsystem and electronic components. A continuous high voltage industrial power supply will be procured. The engine will be assembled on a baseplate suitable for alternative mounting configurations.

2.4 Manufacture of a dynamic test rig

The test rig will be manufactured as a transportable 'stand alone' rig with all the necessary control functions and instrumentation required to carry out demonstration tests. Full data recording will be incorporated.

2.5 Development testing

A programme of development tests will be carried out to confirm performance predictions in a number of design configurations. Higher Q operation and a more optimum thruster geometry is expected to yield higher thrusts.

2.6 Demonstration testing

It is proposed that a number of demonstration tests will be carried out to help convince the space industry that further development of the technology will lead to significant improvements in spacecraft capability.

2.7 Establishment of an EM programme

Throughout this DM programme effort will be directed towards establishing the necessary funding to carry out an EM programme. Both venture capital and Government sources of R&D funds will be actively sought, together with European Commission funds under their sixth Framework programme. Support from ESA will also be investigated.

2.8 Milestones

The objectives are expected to be met over a 3year programme with the following milestones:

	Milestone	Month No.
1.	DM engine design complete	12
2.	Dynamic test rig design complete	12
3.	DM engine manufactured	22
4.	Dynamic test rig manufactured	23
5.	Development test programme complete	30
6.	Demonstration test programme complete	33
7.	EM programme established	36

3. Technical Description

3.1. Engine design

Fig. 1 shows a block diagram of the complete DM engine. The thruster comprises a centre section based on the design of the experimental thruster but machined from aluminium to close tolerances and fine surface finish. To achieve the expected high Q operation, silver plating of the inside surfaces will be necessary. Attached to the centre section are alternative large and small sections which may incorporate tuning plates or dielectric sections. Precision flanges will be used to minimise leakage and EMC problems.

An industrial magnetron will be procured together with the high voltage power supply unit to provide a variable power output from the magnetron. A thermal control system will be designed using a water pump and radiator to provide cooling to the magnetron and isolator.

The magnetron output will be fed via the isolator, a dual coupler and a 3 stub tuner to the centre section of the thruster. Input and reflected power will be monitored via the coupler.

The engine design process will start with a study of the missions planned for launch over the next 10 years. In particular, the orbital requirements, spacecraft mass and electrical power specifications will be reviewed. Typical propulsion system requirements will be derived for different types of missions and an optimum engine specification will be prepared which will ensure maximum utilisation. This optimum requirement specification will then be used to design the DM engine within the constraints of available components.

Existing design software will be used to carry out the detail microwave design from which manufacturing drawings will be prepared. Thermal design will be followed by early procurement of the components required to enable a series of thermal development tests to be carried out. These will be necessary to establish confidence that the engine will run continuously without exceeding safe temperature limits.

3.2 Test rig design

The primary requirement of the test rig is to support the engine with minimum friction and allow it to accelerate in a controlled manner. The acceleration will be recorded and the rig will be capable of calibration. Although the present concept assumes rotational acceleration the possibility of a linear test rig will be investigated.

Fig 2 illustrates the rotary test rig concept with the thruster and high voltage power supply mounted on either side of a turntable arm supported on an air bearing. Power will be fed through slip rings and a telemetry loom will be used initially. When full rotation is achieved a wireless control and telemetry system will be employed. Coarse and fine tachometers will be used to measure angular acceleration.

The turntable arm will be adaptable for use as the beam in a counterbalanced static test rig. All test data will be monitored and recorded on a laptop computer built into the rig. The complete test rig will be capable of transportation for independent testing at any laboratory in Europe.

The test rig design process will start once the major parameters of the engine design are established. The bearing design will dictate the thrust detection threshold for a given engine mass and will become the design driver. A separate design package for the calibration system will be carried out. Systems using balance weights or a compressed air thruster will be investigated.

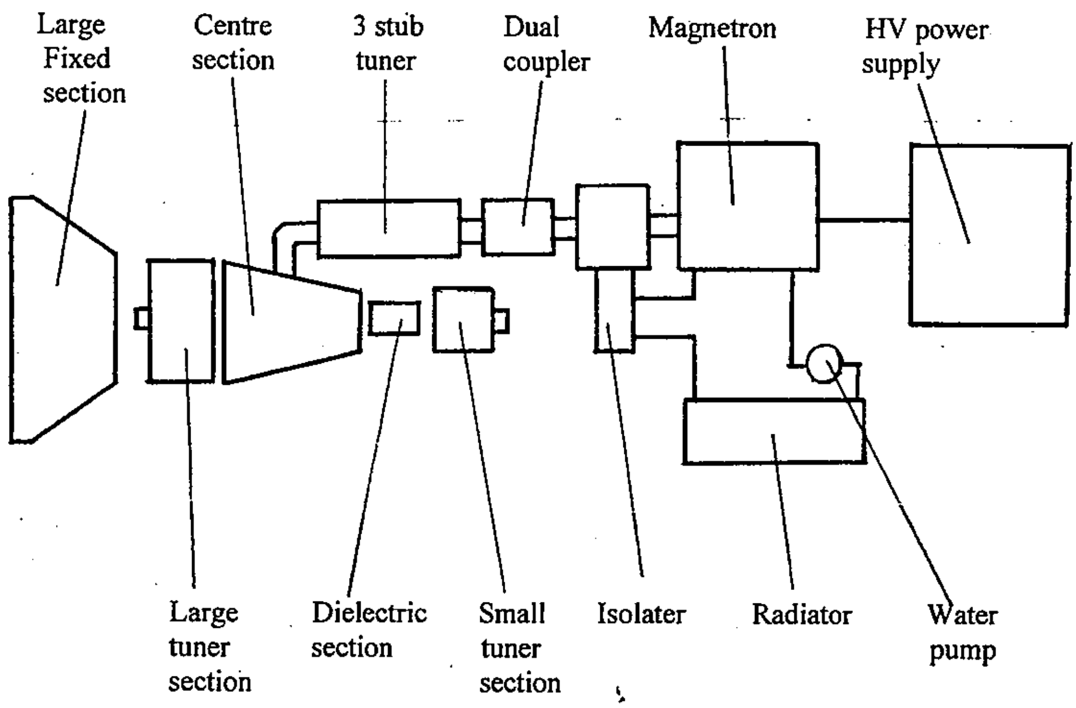


Fig 1 <u>**Block Diagram of DM Engine**</u>

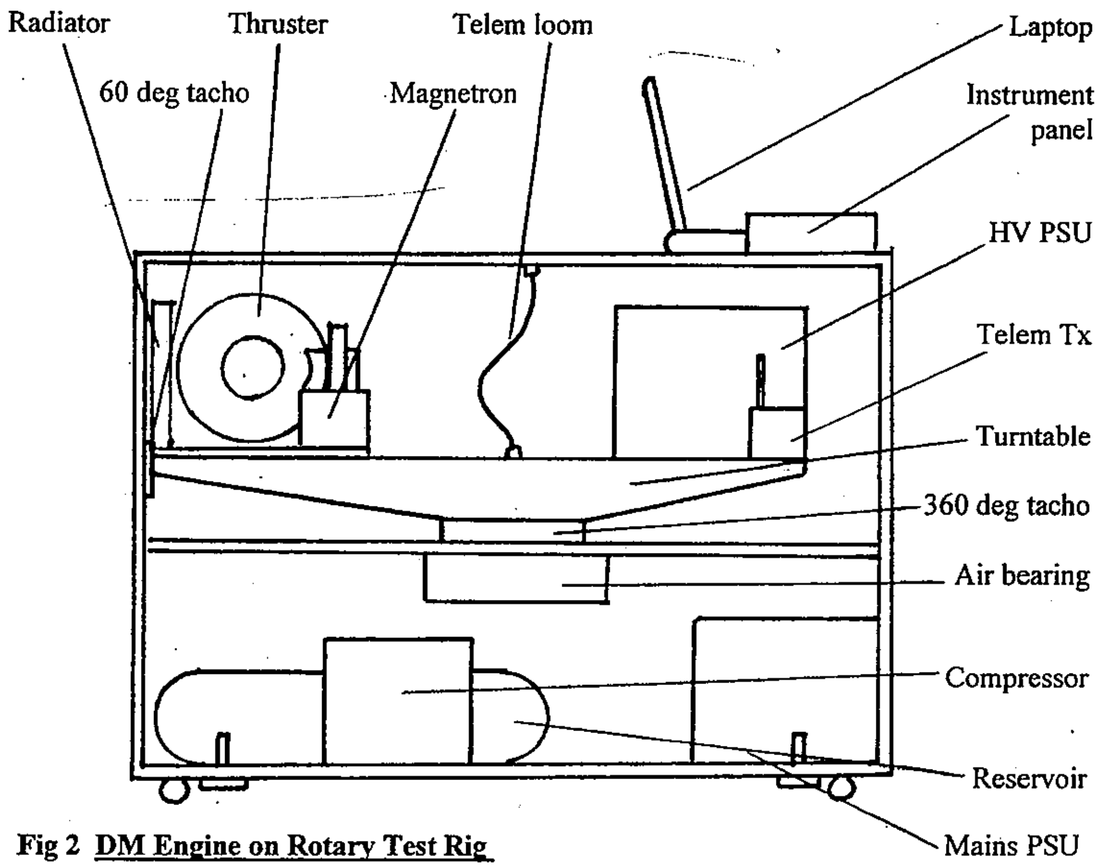


Fig 2 <u>**DM Engine on Rotary Test Rig**</u>

3.3 Engine Manufacture

The thruster sections will be manufactured at a local engineering firm familiar with the requirements of space microwave components. The magnetron, power supply and feed components will be procured from a German supplier of industrial microwave equipment. Early consideration will also be given to the programme necessary to develop a space qualified magnetron which may also draw on the expertise of a German firm, familiar with space TWTA manufacture. All engine assembly will be carried out using SPR workshop facilities.

3.4 Test rig manufacture

Test equipment will be procured from commercial suppliers with specialised test rig components manufactured by local contractors. All test rig assembly and calibration will be carried out by SPR Ltd.

3.5 Development testing

Initial development work will concentrate on the microwave design, with a series of Q measurements being made using a sweep frequency generator. This will be procured as a commercial instrument. The full range of thruster configurations will be tested and the Q will be maximised at the proposed operating frequency (most probably 2540 MHz). Full power testing will follow with the aim of tuning the feed and thruster for maximum power transfer and minimum reflected power. Temperature monitoring of all the critical points in the engine will be carried out together with microwave leakage measurements.

Thrust measurements will be carried out initially using a counterbalanced static test rig. This will employ the balances used in the feasibility study experimental work. Acceleration measurements will then be carried out using the dynamic test rig. Early tests will be over a limited angular range and will be compared to calibration measurements using balance weights. Tests will be carried out over the full power range available from the variable high voltage power supply. Different resonator configurations will be tested, and the thruster itself will be mounted to produce torque in both forward and reverse directions. Also by mounting the thruster with its axis radial to the centre of the test rig, a zero torque test will be carried out to measure any spurious effects.

3.6 Demonstration testing

A test procedure will be developed that is designed specifically to demonstrate the potential of the engine for future spacecraft propulsion. The test will allow the engine to fully rotate the turntable whilst operating at maximum thrust. The objective will be to finally remove any doubts as to viability of the propulsion concept. Demonstration testing could be carried out at any Government or commercial premises throughout Europe and it is hoped that at least one demonstration will occur at an ESA establishment. A video recording of demonstration tests will also be used as a marketing tool.

3.7 Assessment of technical risks

The work proposed will have technical risks in the following areas:-

<u>High Q operation</u> The output thrust of the engine is directly proportional to the operating Q. The experimental thruster used in the feasibility study achieved a Q of 6000. The theoretical Q that could be obtained in the DM engine approaches 50,000. However the actual Q that will be achieved will depend upon maintaining low losses throughout the resonator and in

maintaining thermal stability in the magnetron and feed components. Successful high power operation at high Q will also be dependent on suppressing arc discharges.

Thermal design To achieve continuous operation of the engine it will be essential to maintain a stable thermal balance at temperatures within safe operating limits. Not only must the water cooling of the magnetron and isolator be sufficient but also the thermal paths throughout the thruster must ensure an acceptable thermal profile.

Test rig design The weight of the DM engine and mountings will inevitably cause frictional drag in the bearing system, whichever test rig design is chosen. This will place a limit on the minimum thrust that can be demonstrated and on the acceleration that will be achieved. However assuming a 50Kg mass and a net thrust equal only to the 2g achieved during the feasibility study, a rotation of 1 rpm will be reached after 3 minutes continuous thrust. This would give a clear demonstration of operation.

4. Project Timetable

The project is scheduled to be completed in a 3 year period and will consist of 20 work packages carried out according to the progress chart given in appendix A.

5. Level of Innovation

It has always been recognised that a propulsion technique that does not require reaction mass (propellant) would have a profound effect on the space industry. NASA has an ongoing programme in Breakthrough Propulsion Physics with this as one of its objectives. The feasibility study, through both theoretical analysis and experimental results has shown that for the first time this objective has been met with the microwave engine.

The significant improvements possible in system performance are illustrated by comparing the specified requirements for a typical ESA scientific mission using ion engines (the SMART-1 mission), with the performance of a microwave engine of similar power.

	Ion	**Microwave**	
DC Power	700	700	W
Output thrust	23	39	mN
Thrust time	1.6	15	years
System Mass	94	9	kg

The basic technologies of power supply, magnetron and thruster are each readily capable of space qualification. They are also fundamentally high reliability, electrical technologies, with none of the failure modes associated with chemical or ion propulsion systems.

The technology would also contribute to an overall reduction in toxic chemical exhaust products from present launch systems, and eliminate the safety concerns during propellant loading of current satellites. Microwave engines can be conveniently scaled, with increasing power being implemented at decreased operating frequency (and increased specific thrust.) Engines with power ratings of 100 kW could be designed to operate at UHF frequencies, to provide the primary propulsion for major manned or unmanned missions.

It is confidently predicted that microwave propulsion will become the enabling technology of the space infrastructure for the twenty-first century. It is of strategic importance to the UK, as it will provide the long awaited commercial return in electric propulsion technology investment.

Once the first generation technology has been established, advanced designs employing very high Q techniques will be developed. The high thrust available from these engines would have enormous potential for use in ground and airborne transportation. They would also be particularly suitable for the deflection of near Earth asteroids, as they will provide the controlled long term thrust, for small velocity change, that is the requirement of such missions.

The significance of this concept led to an initial patent application which was granted 5 May 1993, specification number GB2229865. Further theoretical and experimental work led to an improved understanding of the concept which resulted in a second patent being granted 19 April 2000, specification number GB2334761. A copy of this patent is given in Annex B. A search report carried out by the Patent Office for the feasibility study suggests that the work is "at the leading edge of innovation". A copy of the search report is given in Annex C.

It is expected that during the design phase of this project two further patent applications will be made covering high Q technology and further spacecraft applications.

6. Marketing and Commerical Exploitation

Although many of the more exciting applications of microwave engines are longer term, there is a clear short term application of very large commercial benefit.

The engines can be used in the later stages of satellite launches (GEO transfer) and for maintaining operational orbit. The performance of a microwave engine is such that the launch mass of the satellite would be halved and its lifetime significantly extended.

Recent use of ion propulsion has demonstrated that electric propulsion techniques are viable in certain mission applications, however the following comparison table illustrates the considerable cost and performance benefits that microwave propulsion offers to commercial communication satellite operators.

Current propulsion is assumed to be a bipropellant apogee engine and AOCS thrusters whereas the ion propulsion data is based on the latest ESA thruster that will be used in their SMART-1 mission. The microwave system assumes an S band primary engine.

	Current	Ion	Microwave	
Comms Payload Mass	345	345	345	kg
Satellite Launch Mass	3040	1990	1312	kg
Satellite DC Power	6	6	6	kW
Size Height	2.8	2.8	2.8	m
Length	1.7	1.7	1.7	m
Width	2.5	2.5	1.3	m
GEO transfer time	<1	312	36	days
Propulsion System Cost	3.1	41.7	3.9	£million
Total Satellite Cost	57.9	96.5	56.4	£million
Launch Costs	79.8	52.2	34.4	£million
Total Cost	137.7	148.7	90.8	£million

The GEO transfer for current systems assumes a conventional elliptic transfer orbit, whereas the ion and microwave propulsion systems assume a spiral (Edelbaum) transfer from a low Earth orbit. The launch capability and costs are scaled from current data.

The data is based on real space industry costs and when combined with the latest 10 year launch prediction issued by the well respected Teal group, illustrates the commercial potential of the technology.

For GEO satellites alone the predicted 373 launches would save an estimated £15.5 billion. This would be the driver to establish a manufacturing business worth £3.8 billion over 10 years.

This project is the essential background work needed to support a marketing exercise which will be taking place throughout the 3 year period. It is planned to continue the existing efforts to raise awareness of the technology throughout the space industry and to seek funding for an EM programme. This will lead to qualification and flight models designed for specific missions. One particular source of funding that will be investigated is the European sixth Framework Programme. A new feature is the NEST programme (New and Emerging Science and Technology). This is designed "to support unconventional and visionary research that explores new avenues of science and technology".

Work will also be directed towards following up a number of venture capital sources as well as investigating the potential of the Regional Venture Capital Fund.

It is anticipated that the EM programme would last 2 years, during which licensing agreements would be negotiated with organisations wishing to utilise the technology in flight programmes. The primary user group is identified as the major commercial satellite operators and government or international scientific organisations. However there is a secondary group comprising communications and media companies, industrial groups looking towards long term technology changes and the insurance business. Initial contacts made during the market assessment work of the feasibility study will be followed up with particular emphasis in looking towards the European market.

7. Business background and project management

Satellite Propulsion Research Ltd (SPR) was formed in October 2000 to further the research and development of microwave propulsion technology. A SMART funded feasibility study was successfully completed in October 2002 (ref.931).

The present shareholders are:

R J Shawyer C.Eng MIEE Director.
A consultant Engineer with extensive senior technical and managerial experience including 20 years in the space industry. Mr Shawyer is the Inventor of the microwave thruster.

[redacted] Company Secretary.
A Chartered Accountant with many years' experience in providing support for small and medium sized businesses. Most recent experience includes providing strategic planning for SME's; direct support to directors and working with one of the UK's leading private equity advisors.
Primary role is to lead the fund-raising activity; control the company finances and seek out commercial partners for the second stage.

9. Need for SMART support

Although the feasibility study provided clear technical verification of the concept, the difficult theory and complexities of the experimental results have not provided an easily understood demonstration of the technology. This is particularly necessary when investor groups have to decide on the risks inherent in funding such development. There has been a universal appreciation of the possible high commercial return, but a disappointing level of understanding of the technical detail.

It would seem that the ability to provide a visual demonstration of propulsion together with improved performance data will be essential to establish the funding necessary for full engineering development. SMART funding provides the ideal (and perhaps only) mechanism for bridging this credibility gap.

All the existing and new shareholders are fully committed to the development of the technology and have agreed to provide funding loans to support the company during the Demonstration Model development. Although venture capital investment will be actively pursued throughout the project, the shareholders have agreed to receive share options rather than full loan repayment if required.

Copies of the shareholder loan agreements are given in Annex E.

10. Project Costs

A cost summary and cash flow projection are given in Annex F.

[redacted] Marketing Manager.
[redacted] and has 20 years experience of managing the transition from invention to commercial success for many products. Provides marketing and venture capital search expertise for Satellite Propulsion Research Ltd.

[redacted] Technical Advisor.
[redacted] with many years experience of engineering and management of high technology developments. Acts in a technical advisory role for Satellite Propulsion Research Ltd

[redacted] Consultant.
[redacted] Specialist in MHD theory and has considerable experience in space propulsion and nuclear physics. Acts as a consultant for the theoretical aspects of the work.

For this project three new shareholders will join the company.

[redacted] Project Administrator
A senior administrator and secretary, with many years experience working for commercial and government organisations. Will provide budget control, contract administration and secretarial support.

[redacted] European Marketing
The Director of Studies in a language school based in Germany, with 10 years experience of European business practice. Fluent in both German and French, will provide European marketing support.

[redacted] Technician
An electronics téchnician with wide experience of electromechanical and electronic manufacturing including prototype and aerospace asemblies. Will provide technician support during engine assembly and development testing.

CV's of present and new shareholders are given in Annex D.

The project will be managed by R J Shawyer working full time over 3 years. He will carry out the majority of the technical work with support from the other shareholders as indicated. Component manufacturing will be carried out by a specialist engineering company. Rigorous schedule and budget control will be applied with reporting to SBS every 3 months.

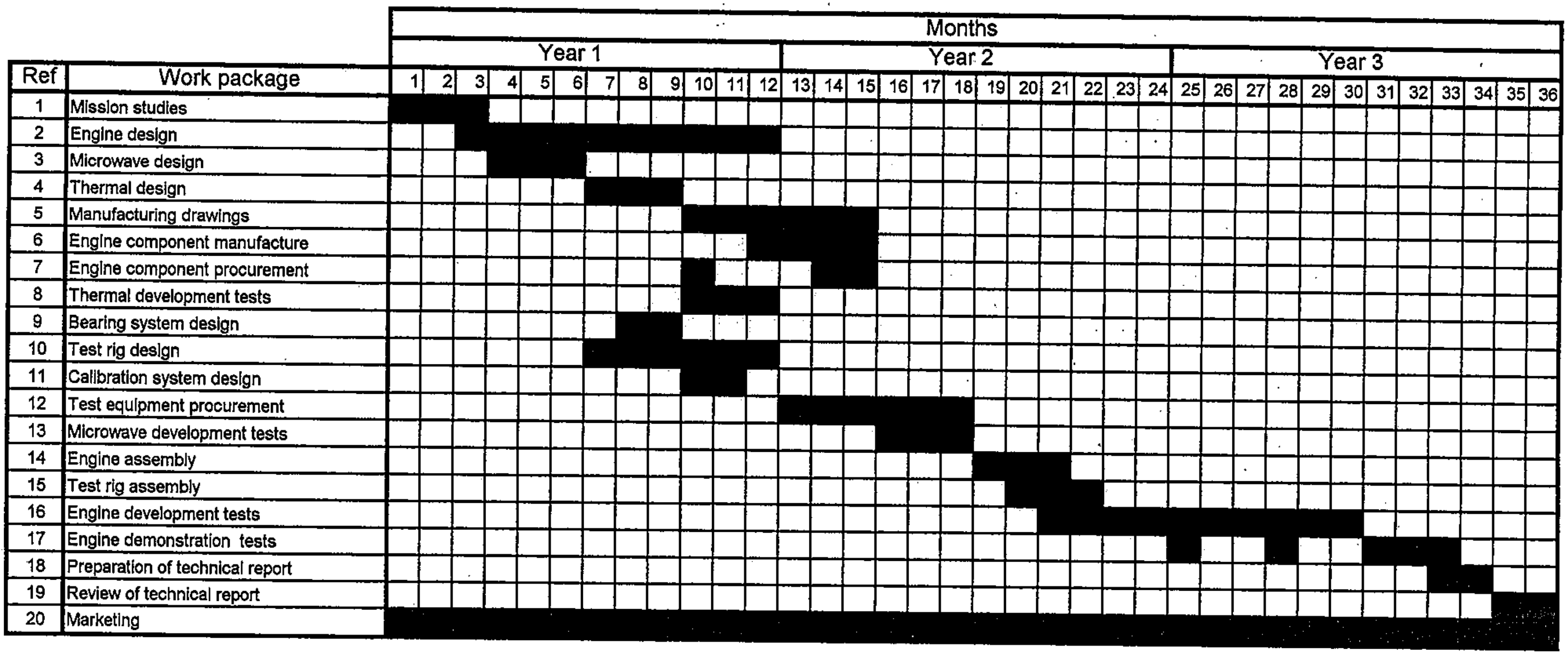
8. Use of available Funds

SPR Ltd has no other activity requiring funds other than the central aim of furthering microwave propulsion technology. In the last two years £58,000 have been spent on the feasibility study. The SPR board has authorised the spending of £259,960 over the next three years on the development of a demonstration model of the microwave engine. £156,000 of this will be used to pay for the Engineering work together with project management, project administration and financial management. Company overheads will be kept to an absolute minimum, estimated to be £21,960. A total of £54,500 will be spent on materials, subcontract and technical consultancy as well as the test programme. Finally £27,500 is planned for the marketing work. The work packages comprising this project will be the first priority of SPR Ltd.

Satellite Propulsion Research Ltd

ANNEX A

Demonstration Model Schedule



Work completed
Work to be undertaken