THE PPS 1350 PROGRAM

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ABSTRACT

A new SPT thruster is jointly developed by FAKEL and SEP. It is intended to suit the new requirements of the prime contractors: increased total impulse, slightly higher specific impulse, more severe vibration specifications. The PPS 1350 is intended to fly on the experimental spacecraft STENTOR in 2000. PPS 1350 means: Propulseur à Plasma Stationnaire, 1350 Watt power.

The technical design of this new thruster inherits of the best design experience accumulated at FAKEL and SEP. In order to insure the highest possible life, the PPS 1350 operates in spike mode (it is also able to operate in focused mode). [1], [3]

A Development Model has been recently tested during 3500 hours at SEP, accumulating 1.1 MN.s total impulse, while a second thruster has been tested 1000 h at FAKEL for a slightly different operating point.

The ceramic erosion is similar to the one of SPT 100, despite the higher discharge voltage and power. The erosion of the redundant cathode is negligible and the one of active cathode is very small. From these results the required lifetime can be safely extrapolated.

INTRODUCTION

The mass and power of telecommunication spacecrafts is steadily increasing. In 1992, the total impulse of the SPT 100 - one MN.s - seemed more than sufficient for all foreseeable spacecrafts, thus enabling to perform NSSK on a 2 tons satellite (BOL) during 15 years.

Not only the mass increase pushes the total impulse requirement beyond one MN.s, but the users want to use the thruster also for orbit injection.

The users wanted also to increase vibration resistance of the thruster in order to have more freedom of design for the spacecraft structure.

The specification of the new thruster was established by an integrated team including the potential users.

From the technical point of view, life extension was favoured over reduced divergence.

Since, the first flight is scheduled for STENTOR, the development time is constrained and only proven and reliable solutions could be used

REQUIREMENTS

The requirements have been established by an integrated team including CNES, AEROSPATIALE, MMS and SEP. The power level was increased to 1500 W to suit requirements. The table 1 summarises the thruster specification.

Table 1

PPS 1350 functional specifications

Reference thrust	88 mN
Discharge voltage	350 V
Propellant flowrate	5.2 mg/s
Discharge power	1500 W
Specific impulse	1720 s
Specific power	17 W/mN
Total efficiency	51 %
Total impulse	1.44 MN.s
Operating cycles	5200
Divergence angle	42°

PPS 1350 environmental specifications

Temperature:	
Operating	-43, +205 °C
Qualification	-48, +210 °C
Random vibrations:	
Acceptance	10.7 g rms.
Qualification	16 g rms.
Sinus vibrations:	
Acceptance	
5 - 21 Hz	5 mm
21 - 100 Hz	12 g
Qualification	
5 - 21 Hz	10 mm
21 - 100 Hz	18 g
Shock:	590 g peak, 0.25 ms
Acoustic noise:	146.5 dB

as it can be seen in table 1, almost all PPS 1350 requirements are more severe than the ones of existing CED thrusters.
Unless otherwise specified, the values are related to the nominal operating point. In fact, the thruster is throttlable in a wide range and can be also operated at 300 V.
The 1.44 MN.s total impulse specification corresponds to roughly 4600 hours of operation. For a two tons spacecraft equipped with two thrusters canted at 45 ° angle, this corresponds to a ΔV of 1000 m/s. This can be split between NSSK (750 m/s for 15 years) and end of orbit injection (250 m/s).
With a 1.5 qualification factor, the life test duration would be 6900 hours with 7800 cycles. Accordingly, a 7000 h life test is foreseen in the development plan.
The more severe shock and vibrations requirements could only be accommodated by a mechanical redesign (anode block and cathode).
Another very important requirement is related to the industrial organisation: the thruster must be producible in parallel at FAKEL and SEP. Since many materials and processes are specific to Russia, SEP developed western equivalent when needed.

PPS 1350 TECHNICAL DESCRIPTION

The thruster blends the proprietary concepts of the FAKEL and SEP SPT designs. It uses four external coils like the SPT 100 and a supplementary coil at thruster back to insure a zero magnetic field point near the anode like SPT Mk II. [3]
The coil technology uses mineral insulation sheathed wires in order to eliminate possible outgassing and to increase thermal margin (already very high).
In what concerns the redundant cathode erosion problem, discovered during the SPT 100 endurance tests [2], the R and D works performed inside ISTI by RIAME enabled to define practical rules to lower the erosion rate.
This was implemented in the PPS 1350 cathode mounting (reduced cathode - thruster axis angle).
The cathode design - although extrapolated from the SPT 100 cathode design - is a new one: the structure is reinforced to handle higher vibration level and the ignitor is thickened to improve its erosion resistance. The heater mounting is also modified.
The anode block is redesigned to improve vibration resistance. The first natural frequency is specified above 200 Hz.
The figure 1 shows the thruster layout.

DEVELOPMENT PLAN

The PPS 1350 development plan is linked to the STENTOR plasma propulsion subsystem development plan. The propulsion subsystem includes three types of modules:
* the xenon storage and distribution module,
* the electrical module,
* the thrusters modules.

Each thruster module includes two thrusters and one orientation mechanism.
The main electrical module equipment is the PPU (developed by ALCATEL - ETCA under ESA contract).. Interface tests between PPU, Filter Unit and thruster are obviously needed early in the program and have been already performed with an SPT 100 in a first time.
The development plan of the PPS 1350 itself is a classical DM, EM., QM. model philosophy. The figure 1 shows the development schedule.
The development plan is divided in three phases:

* Phase 1: (start of work to PDR)
- Development of technologies (cathode, anode block)
- Functional optimisation
- Mechanical design
- Mechanical and thermal finite elements models, magnetic model.
- Cathode prototypes manufacturing and testing,
- Cathode heater cycling tests (10 000 cycles).
- DM manufacturing and 1000 h testing at FAKEL
- DM manufacturing and testing at SEP: performance mapping, 1000 h endurance test (extended to 3500 h).

* Phase 2: (PDR to CDR)
- EM manufacturing and 3500 h testing at FAKEL
- EM manufacturing and 3500 h testing at SEP, extended to 7000 h .
- EM / PPU interface testing.
- Third EM model vibrations and environmental tests at SEP.
- Follow-on cathode tests.
- CDR preparation.

* Phase 3: (CDR to qualification)
- QM manufacturing and 7000 h testing at FAKEL
- Manufacturing of STENTOR Flight Models immediately after CDR.
- Qualification Review documentation Preparation.
- Qualification review at end of SEP 7000 h test on EM.

Due to the long duration of the EM / QM life tests, the FM manufacturing starts before the end of life tests. The two FMs should be delivered at least one year before launch as the STENTOR platform will undergo extensive ground tests before launch.

DEVELOPMENT TESTS:

Several thrusters configurations has been tested at FAKEL and SEP, the magnetic field pattern of each configuration being computed by SEP. After this first phase, a configuration has been selected and manufactured. The functional tests revealed no problem.
In parallel, a SPT 100 sustained PPU coupling tests and ESD simulation tests. All tests were successful. Especially, the thruster starting transient doesn't generate ESD when an electrostatically charged sphere is exposed in the vacuum chamber. Small differences are expected with PPS 1350.

Two SEP built PPS 1350 cathodes were tested on a SPT 100 to measure their characteristics.
In parallel, several cathode heaters were submitted to 10 000 "dry" thermal cycles in an UHV chamber.

PRELIMINARY ENDURANCE TESTS RESULTS

It was planned in the development plan to perform two parallel endurance tests at FAKEL and SEP of 1000 h each. The test conditions are slightly different in order to enable to identify the "facility effects" in thrust performances. The operating points of the thrusters were also different. Operation at the same point were performed at regular intervals in order to identify separately the facility effect.

SEP Test

Test facility - test conditions:

The test facility LIB is especially designed for endurance tests (figure 3). Its length is 5 m and maximum diameter is 3 m. The conical shape provides the best compromise between chamber cost and reduced back sputtering. To reduce further back sputtering, the ion beam impinges on SEPCARB ® carbon - carbon plates.
The pumping is insured by a purpose built cryogenic pump giving a pumping speed of 40 000 l/s for xenon.
The thruster can be isolated inside an airlock evacuated by a turbomolecular pump.
The thruster is mounted on a a thrust balance itself mounted on a moving cart putting the thruster in firing position.
The thrust measurement is given by the coil current of a force motor slaved to maintain the balance moving part to a reference position.
A probe arm is devoted to beam diagnostic. The arm handles 12 Faraday cups and five RPA. Its coverage is greater than 70° half angle. Each Faraday cup includes an entrance collimator. Both cup and collimator are built from carbon to reduce sputter erosion and secondary electron emission. The collimator helps to eliminate slow ions scattered from the beam by collisions with neutral gas
High purity xenon is supplied to cathodes and anode by purpose built equipment including regulating mass flowmeters.
The facility is controlled by a HP 700 workstation connected to two data acquisition and control systems.
The workstation emulates the discharge current control loop of the PPU, acting on the mass flowmeter and insures all other control functions of the PPU, including starting sequence.. Should a vacuum facility or xenon supply malfunction occur, the thruster is automatically switched off.

The test was performed in an automatic mode, day and night and also during week ends and holidays. The magnet trim was not used. The thruster was not re-optimised during test.

The endurance test showed the dependability of the facility:
* During 3500 h only three stops were caused by the facility (one mains supply power down and two water supply failures).
* The cryogenic pump was operated during up to 762 h without regeneration, storing more than 15 kg of xenon.
* The average firing time was 22.58 hours per calendar day (i.e. 94 %).

Tests results

The results obtained at SEP at 1000 h were very good, so it was decided to push the test duration to 3500 h (this was initially foreseen at the EM stage) in order to be able to predict very early the effective thruster life.
The test started on January 30 and was stopped on July 4, including 112 cycles.
The figure 4 shows the thrust versus time. The integrated signal of the Faraday cups shows a fairly good correlation with thrust. The thrust drops from

89 to 87 mN after 100 h then decreases slowly to 86 mN at 1500 h and increases to 88 mN at 3000 h.
A similar behaviour is observed on SPT 100 but the thrust decrease is more pronounced. The figure 5 shows the efficiency versus time displaying the same behaviour than the thrust. The average Isp during the test was 1650 h.
The initial divergence half angle (42°) decreases slowly to 40° during test.
The discharge current oscillations increase up to 400h, are constant (1.2 A) between 400 and 1200 h and decrease monotonically to 0.5 A at 3500h.. The cathode coupling voltage is located between -14 and -16 V: the mounting angle modification had no impact on coupling voltage.
The figure 6 shows the ceramic erosion versus time, measured from photos, compared to erosion profile measured at JPL on SPT 100 # 3. It can be seen that the erosion profile on inner ceramic is similar, while the erosion is slower on external ceramic. The external pole piece shows only minor dents at 3500 h.

FAKEL Test

Test facility - test conditions:

The test was performed at a lower power (1400 W instead of 1500 W), less favourable to the performance but potentially better for the ceramic erosion. The coils current was regularly re-optimised in order to increase the performances and eliminate if possible the adverse effect of erosion on performances.
The test was performed in the large vacuum chamber used for the SPT 100 western qualification test. Cryogenic pumps were used.
The test was conducted by operators.

Test results

The thrust versus time is shown on figure 7.
Except for one point at 364 h (before re-optimisation) the thrust is always greater than 82 mN. With optimisation, the performance at 500 h exceeds the BOL performance. The figure 8 shows the Isp versus time.(1700 s on average, i.e. better than without re-optimisation).
The discharge current oscillations are lower than 200 mA rms. in the optimised mode.
When compared to SEP tests without re-optimisation, this shows that the average performance can be improved by a controlled use of magnet trim.

CONCLUSION

The PPS 1350 development program progresses smoothly. The PDR was successfully held. The extension of the first endurance test from 1000 to 3500 h gives a good confidence in the design. In addition, it shows that the thruster life (and also cathodes life) will be greater than the one of SPT 100 - which offer already the highest demonstrated life of all CED thrusters - despite the higher ion energy and power.
The systematic testing with PPU along the program will help to eliminate hidden compatibility problems.
The present results allow to consider with some confidence the future flight on STENTOR.

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Last, the authors wish to thank CNES for their support of the PPS 1350 selection on STENTOR and ISTI members for their useful remarks and suggestions.

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[2] W. KIM et Al.
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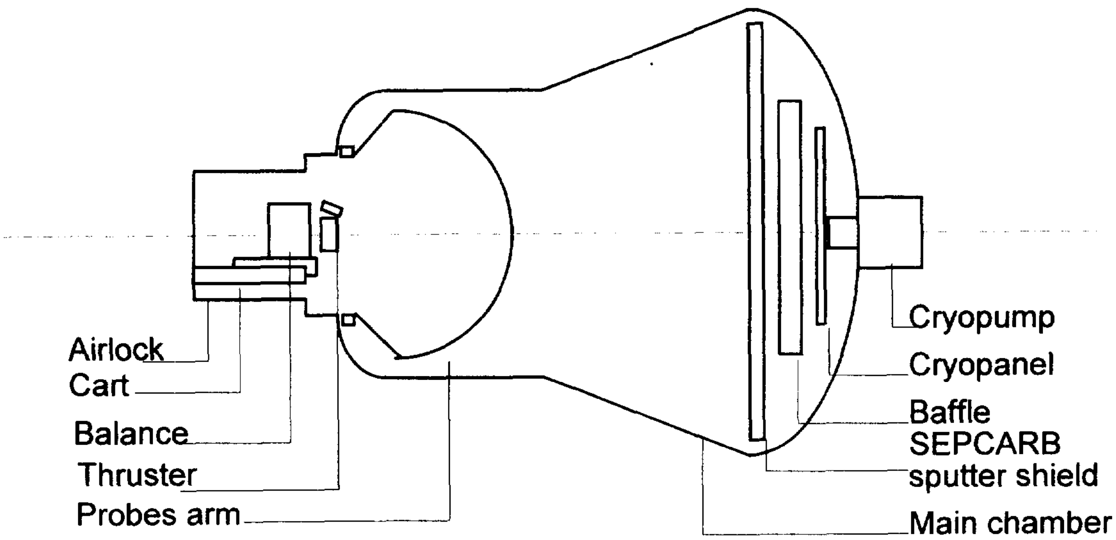


Figure 3: LIB test facility

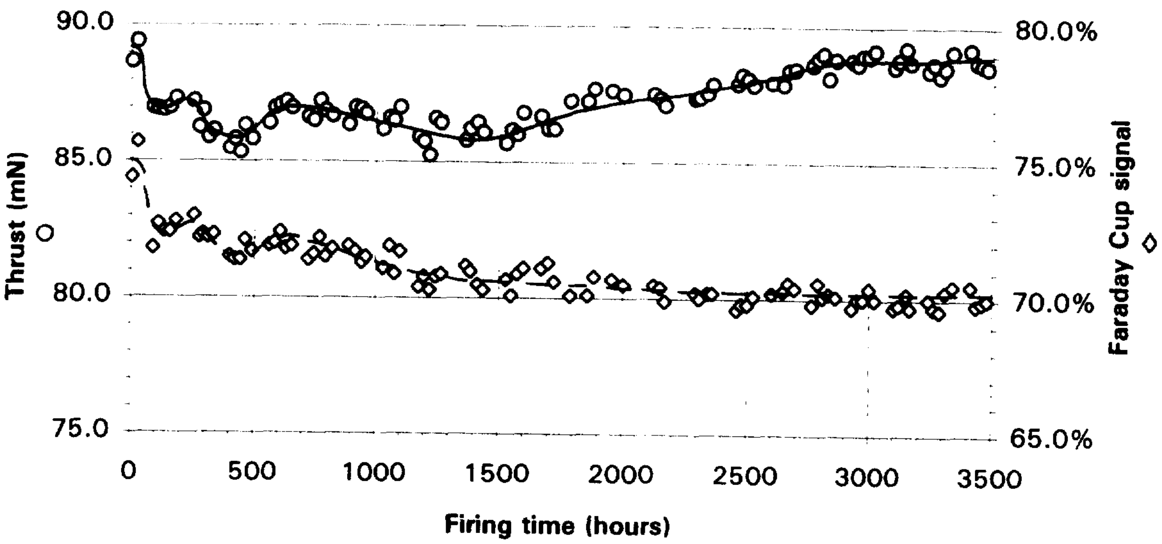
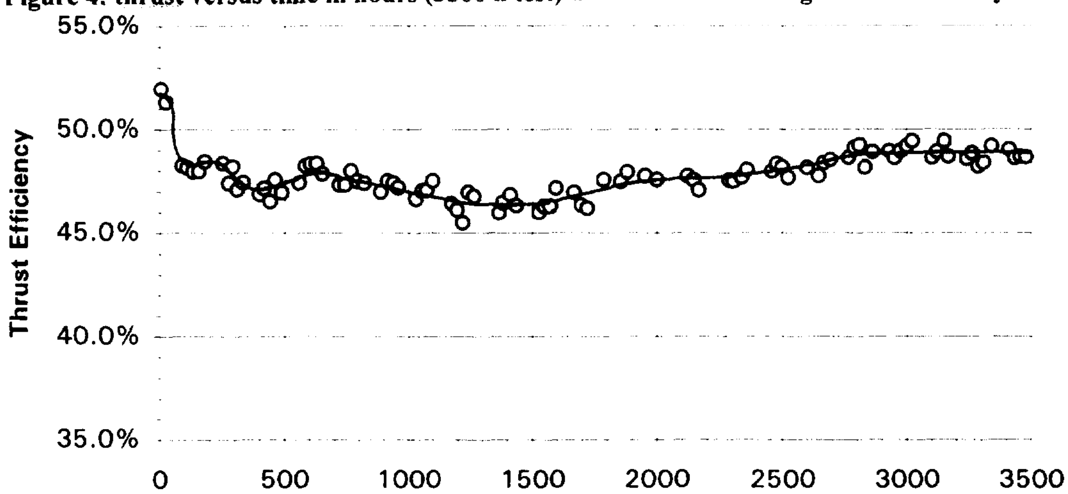


Figure 4: thrust versus time in hours (3500 h test) ⇑

⇓ Figure 5: Efficiency versus time



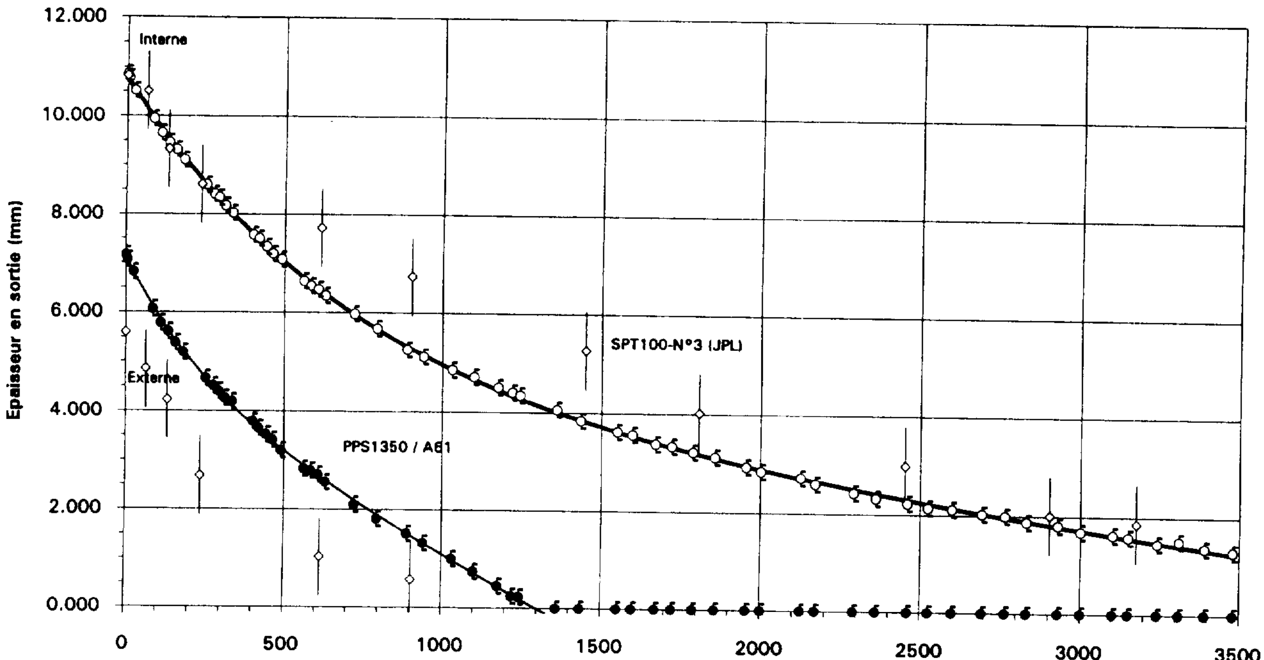


Figure 6: ceramic erosion versus time

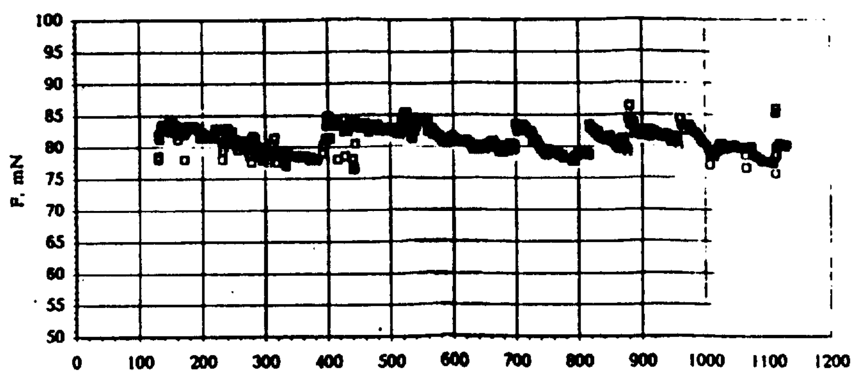


Figure 7: Thrust versus time (FAKEL test)

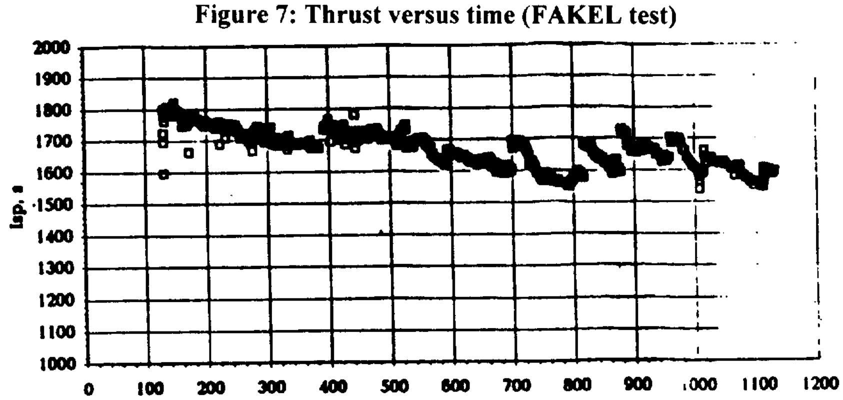


Figure 8: Isp versus time (FAKEL test)

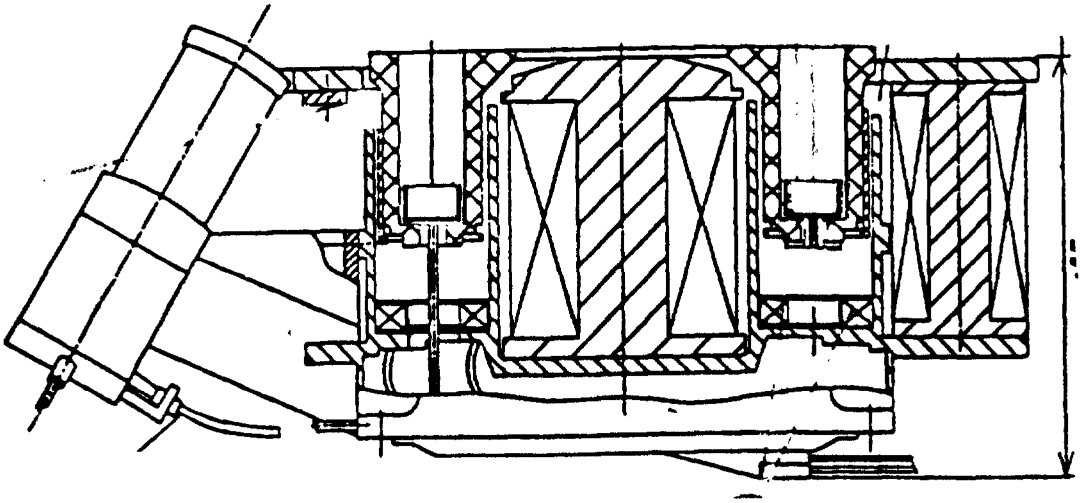


Figure 1: Thruster layout

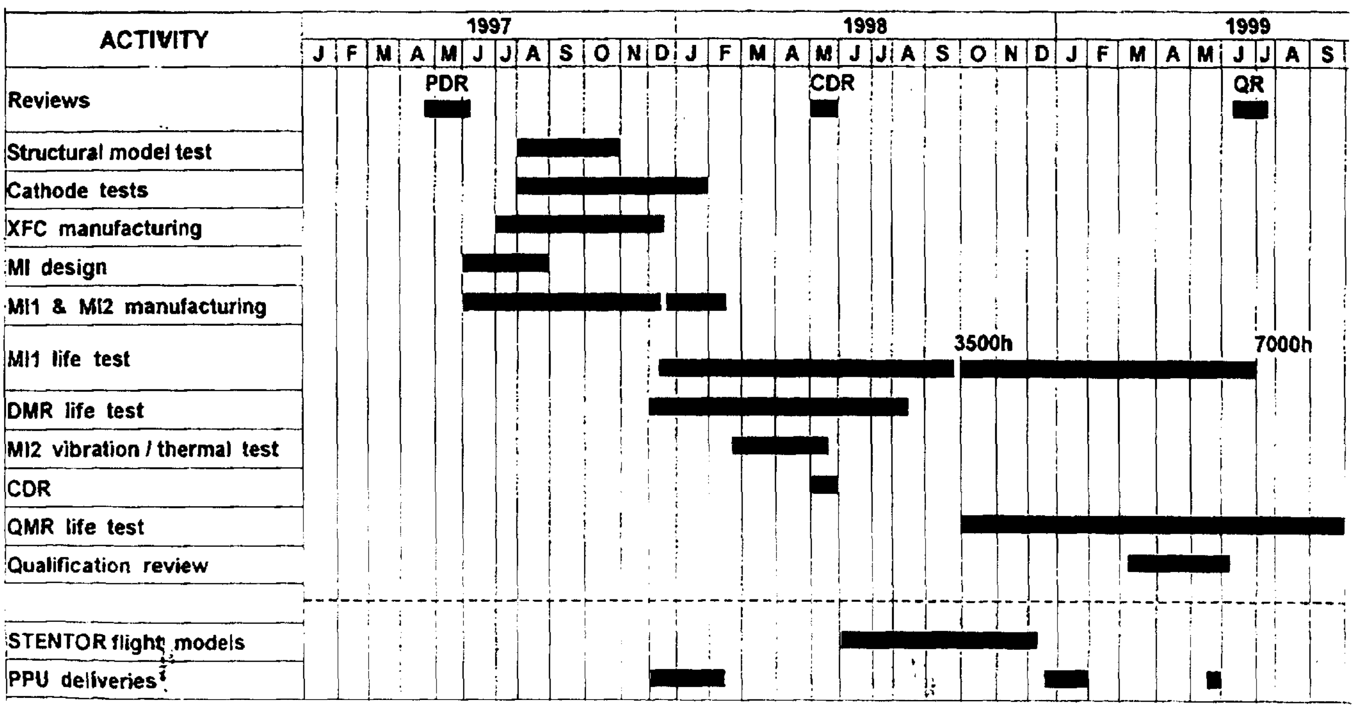


Figure 2: Development schedule