# Development of an Engineering Model of 1 kW Hydrazine Arcjet System

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## Abstract

An engineering model of 1 kW DC arcjet system was designed and has been manufactured. The system consists of a thruster assembly and a power supply unit. The thruster is assembled with a discharge chamber and a gas generator. The chamber is constructed with cathode made of thoriated tungsten and co-axial anode of tungsten. The generator includes a catalyst bed, which decomposes hydrazine into hydrogen and nitrogen gases supplied into the discharge chamber. The thruster and the gas generator are assembled in a bracket and will be tested for verifying thrust and mechanical performances.

The power supply unit (PCU) has been developed by improving a trial product in order to enhance impedance characteristics with the thruster and to reduce its cost. The PCU will be also tested to confirm the improvements.

## Introduction

Ishikawajima-Harima Heavy Industries Co., Ltd. (IHI) has been mainly developing and supplying Reaction Control Systems (RCS) for NASDA in Japan. And IHI also has been doing R & D of bipropellant thrusters and electric propulsion systems as higher performance type of monopropellant hydrazine thruster. The former includes line-up of thrust levels ranged from 500 N to 22N. The later includes electro-thermal thrusters and magneto-plasma-dynamic (MPD) thruster. Electro-thermal thrusters consist of electro-thermal hydrazine thruster (EHT) and DC arcjet thruster.

IHI has succeeded in developing Unified Propulsion System (UPS). The UPS system is composed of a bipropellant apogee engine and monopropellant thrusters, both of which use hydrazine as propellant So, the UPS can simplify the propulsion system by using a common propellant supply system between apogee engine and monopropellant thrusters and reduce its cost. For higher performance system, the electric propulsion can be used as north-south station keeping thruster for GEO satellite instead of monopropellant thruster. The electric propulsion system is to be a key component of UPS.

The activity of electric propulsion system in IHI is as follows. The EHT has successfully been tested on ground and onboard the ETS-VI satellite. The MPD arcjet systems have been successfully performed onboard ISAS satellites of MS-T4 and SFU.[1]

The DC arcjet system has been studied and developed since 1984 in collaboration with Osaka University. Some fundamental thrust performance data have been obtained for designing thruster and power control unit. On basis of these inhouse studies, a study under contract of NASDA was conducted from 1993 to 1998, where thrust performance and endurance data of a bread-board model (BBM) thruster and design data of system were obtained. From these results, an engineering model of the DC arcjet system has been designed.

This paper describes the present status of DC arcjet development.

## Design

The DC arcjet system is constructed with the following components;

1) a thruster assembly,
2) a power control unit (PCU), and
3) power cables.

The propellant is assumed to be supplied from the common propellant supply system.

In the thruster assembly, hydrazine as propellant is decomposed through a gas generator into a hot gas, which is heated by arc current in a discharge chamber and exhausted through nozzle to produce thrust. The PCU supplies some electric power to the thruster for discharging. The discharge power includes a trigger one and a steady one. The former is a pulse mode with high voltage of 1 kV and more and the later a steady mode with low voltage of about 100 V.

The target specification of DC arcjet system is shown in Table 1.

## Thruster Assembly

The conceptual structure of thruster module is depicted in Fig. 1. The thruster assembly is constructed with a thruster head, a gas generator, a hydrazine flow controller and a bracket. The major issues in developing a flight model of thruster are thermal design and life performance. The thermal design consists of two important points of limiting electrode temperatures and heat fluxes into vehicle structure. The life performance depends on endurance ones of electrodes and gas generator.

### Structure

The thruster head consists of the following parts, a discharge chamber, a body and an electrical connector, as shown in Fig. 2. The configuration of thruster discharge chamber is the same as BBM and the same thruster performance can be expected.

### Thermal design

The design point of thermal characteristics is shown in Fig. 3, which is estimated from the thermal balance of the system. The analysis result shows that the thruster head is invested with a discharge power of 900 W and an enthalpy of propellant gas of about 22 W. The output energy is estimated to include a heat flux of 142 W radiated from the surface of electrode surfaces and 30 W conducted into vehicle structure. From the thermal analysis, the temperatures of anode and cathode electrodes are found to be increased up to about 1000 deg C and 1100 deg C, respectively.

The anode electrode is made from pure tungsten with high heat-resisting characteristics. The outer surface of the anode electrode is treated to enhance thermal radiation performance. The configuration of the electrode is also designed with having a thermal choked portion in order to prevent the heat of the electrode conducting up to the electric connector. The insulators are made from boron nitride with performances of high chemical stability, high heat-resisting characteristics and high thermal shock resistance. The material has also such high thermal conductivity that the heat generated in the electrodes can be removed. The body is designed to have sufficient strength to support the weight of electrodes and to prevent the heat of the electrodes conducting up to the electric connector.

### Firing performance

The configuration of thruster discharge chamber is the same as BBM and the thrust performance can be expected as shown in Fig. 4.[2] Thrust performance of 0.11 N and more can be expected at input power of 900 W. From the system firing test using the BBM thruster and PCU, the firing performances as shown in Fig. 5 can be expected. And any unstable phenomenon of discharge and any deterioration of thrust performance are to be found.

### Life characteristics

The life performance depends on the erosion characteristics of electrodes of discharge chamber and the life of gas generator.

The configurations of cathode electrode before and after the endurance firing test of 100 hours are shown in Figs. 6.[2] A relation between the electrode erosion and firing time is shown in Table 2.[2] The erosion quantity of anode electrode is evaluated to be about 16 mg and that of cathode electrode to be about 3 mg after 1000 hr operation. The quantities were so small that the endurance performance of more than 1000 hr can be expected.

In the 100 hr firing test, it was found that some bubbles existing in hydrazine between the flow controller and gas generator might increase the electrode erosion. When some bubbles were mingled in hydrazine, it was monitored that the low mode discharge was long at initial arc discharge. The time of low mode is increased and the electrode erosion is rapidly increased.

The life performance of thruster depends strongly on that of gas generator. Shortage of propellant flow rate may cause the electrode erosion and shorten the electrode life. The gas generator has the same structure as that of monopropellant hydrazine thruster, including a catalyst bed and an injector. The former decomposes hydrazine into hot mixture gas of nitrogen and hydrogen. The later controls the configuration of hydrazine flow injected into the catalyst bed to get high performance of hydrazine decomposition. The conventional gas generators are used to decompose hydrazine flow with more than 0.5g/s. The studies of gas generator reported that, in the case of the extremely small flow rate of hydrazine, the endurance performance of gas generator is deteriorated by heating a feed tube, where some non-volatile residue is produced in the tube and stop the hydrazine flow. The deterioration induces a decrease of propellant flow rate and the electrode erosion.

We have conducted endurance tests summed up more than 200 hours with using domestic hydrazine. The grade of domestic hydrazine is monopropellant one but its main impurity is different from that of imported monopropellant grade hydrazine. The gas flow values before and after 200-hour operation are plotted in Fig. 7. Any serious deterioration was not found in the performance of gas generator after the 200 hours endurance test. The test results may show us a possibility if the gas generator using the domestic hydrazine could have an endurance performance of more than 1000 hours. In the qualification test, a 1000-hour endurance test will be conducted to confirm the endurance performance.

On the other hand, a plenum system has been studied as a countermeasure against the deterioration. The plenum system consists of a gas generator and a reservoir, as shown in Fig. 8. Using the plenum system can allow the gas generator operating at the same condition as normal hydrazine thruster and can maintain the sufficient endurance performance of gas generator. So, the plenum system will be also developed as a backup system.

## Power Control Unit

The power control unit (PCU) is supplied electrical power from the bus power source and supplies the regulated power to the thruster. The PCU BBM is shown in Fig. 9. The functional block diagram of PCU is depicted in Fig. 10. The PCU has two functions of initial arc discharge and continuous steady discharge. The initial arc power is supplied at a pulse train with high voltage of 1 kV and more. The steady arc power is supplied with dual feedback controls. One is a quick feedback for constant current control and the other is a slow feedback for constant power control. The efficiency is 90 % and more at operation with the load impedance of about 13 Ω and more.

The issues in designing a flight hardware are small-sizing, lightening and cost-saving.

### Reducing weight and size of PCU

The weight and size of PCU almost depend on the power devices. Main power devices consist of the following parts;

(1) semi-conductor parts (transistors and diodes),
(2) magnetic parts (transformers and inductors) and
(3) the others (resistors, condensers and et al).

Lightening and small-sizing power devices seem to be hard since both are to increase the costs of devices due to being newly developed.

The possible method for lightening and small-sizing PCU should be realized in system design. One possible method is to operate a pair of thrusters with one PCU.

The diagram of power lines between PCU and thruster is shown in Fig. 11. The main and secondary power lines can be alternated by a high voltage switching relay in PCU. This PCU can reduce the weight by about 25 % and the size by about 40 %.

### Cost-saving of PCU

Methods of reducing the cost of PCU are as follows;

(1) to reduce the number of electrical parts,
(2) to shorten working times for assembly and test and
(3) to use cheaper parts.

Reducing the number of PCU from two to one can satisfy the above-mentioned requirements, (1) and (2).

The equipment whose malfunction affects seriously the performance of whole vehicle system shall be constructed with highly qualified parts (class S) for space application. But usage of the classified parts has made expensive the cost of electrical equipment. On the other hand, a cost-down on space applied equipment has been done by using commercial parts.

Reducing the number of PCU can not be compatible with using low qualified parts. In order to get the minimum qualification of electrical parts, it is recommended to apply relatively low-priced but highly qualified electrical parts of Grade 2 of MIL-STD-975 to PCU, assuming that an aging of PCU just assembled is to be done for eliminating initial malfunction.

## Development Plan

In order to confirm the components and system satisfying the specification, the following tests are planned.

### Test Plan of Thruster

The following tests shall be carried out to obtain the data of characteristics and performance of the thruster;

①function tests (pressure and leak),
②firing test (thrust performance),
③thermal test (firing at maximum temperature condition and correlating thermal model),
④vibration test (strength and resonance frequency) and
⑤endurance test (firing).

The main problems are thermal and strength characteristics. The discharge head is designed to limit heating the electrodes up and conducting heat flux to electric power connector. The design propriety can be confirmed by the thermal vacuum firing test. The thermal model of thruster will be correlated by the thermal data obtained from the thermal balance test.

The strength of thruster module will be confirmed by vibration test at qualification level. Another objective of the vibration test is to obtain the characteristics of resonance frequency of thruster module.

The endurance firing test shall be conducted to obtain the erosion data of electrodes and insulators of discharge head. The endurance test is to be carried out in the system test.

### Test plan of Power Control Unit

In the case of using electrical parts qualified with Grade 2 of MIL-STD-975, a qualification test shall be conducted according to the test flow as shown in Fig. 12. But the electrical parts qualified in the test flow have not been proved in flight application. It is recommended that the electrical parts qualified in the flow shall be tested if the parts could work normally on orbit.

### System Test Plan

The system test will be carried out by assembling the components, including the thruster module and the power control unit. The test consists of the following test;

①functional test,
②firing test and
③EMI test.

In the functional test, the data of interface characteristics between the thruster and the PCU will be obtained. The system firing test will confirm an operation capability in the system configuration and submit the data of thrust and endurance performance of the system. And the EMI data will be also obtained in the system configuration.

### Schedule

The test schedule is shown in Table 3. Component tests have just been started.

## Conclusion

Based on the result of study on 1 kW-class DC arcjet system since 1984, a flight-type model has been developed as a monopropellant hydrazine thruster with improved thrust performance. Assembly and test of the model will be proceeded at soon.

However the mission target is not set yet, prepared is a proposal of onboard operation test. The objective of the development of this system is to supply a DC arcjet system with low power and low price.

## Reference

1)H. Suzuki, H. Sakaguchi, M. Miyata, T. Ohtsuka and K. Uematsu, "EPEX Flight Test Onboard SFU-1 –Thruster, Propellant Supply System and Thermal Control System-", 20th International Symposium on Space Technology and Science, 1996.

2)M. Ishii, K. Kato, T. Ohtsuka, H. Suzuki, K. Kajiwara and A. Hattori,"Operational Characteristics of 1kW Hydrazine DC Arcjet System", 26th International Electric propulsion Conference, 1999.

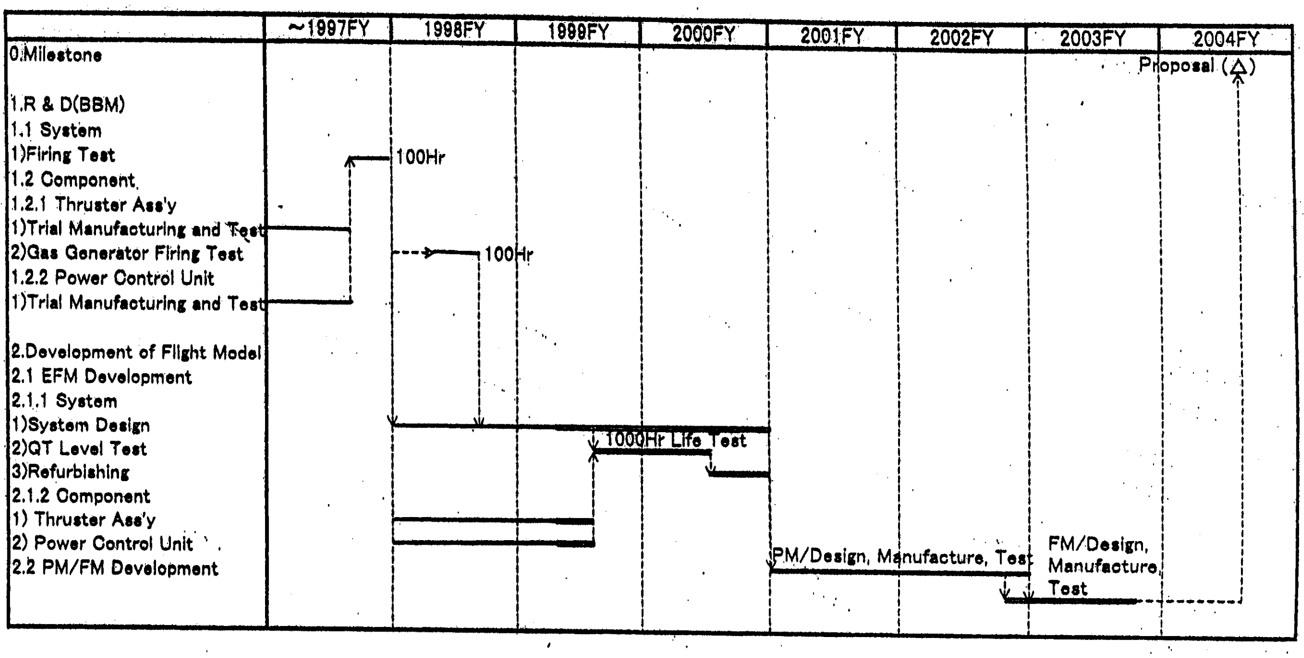
Table 1 Target specification of 1kW DC arcjet system

| Hardware | Item | Specification |
|---|---|---|
| System | Mission duration | 10 years |
| | Operation time | 1000 hours |
| | Starts | 700 times |
| Thruster | Thrust | 0.09~0.13 N |
| | Specific Impulse | 500 s MIN |
| | Power Consumption | 900 W NOM |
| | Weight | 1.5 kg |
| Power Contrl Unit | Input Voltage | 48~50 Vdc |
| | Input Power | 1000 W |
| | Output Power | 900 W |
| | Output Channel | 2 ch |
| | Efficiency | 90 % |
| | Weight | 5.0 kg |

Table 2 Electrode erosion characteristics

| Electrode | Firing Time | Erosion Rate |
|---|---|---|
| Anode | 100 hr | 0.0008 μg/s |
| Cathode | | 0.004 μg/s |

Table 3 Schedule of 1kW DC Arcjet Development (draft)



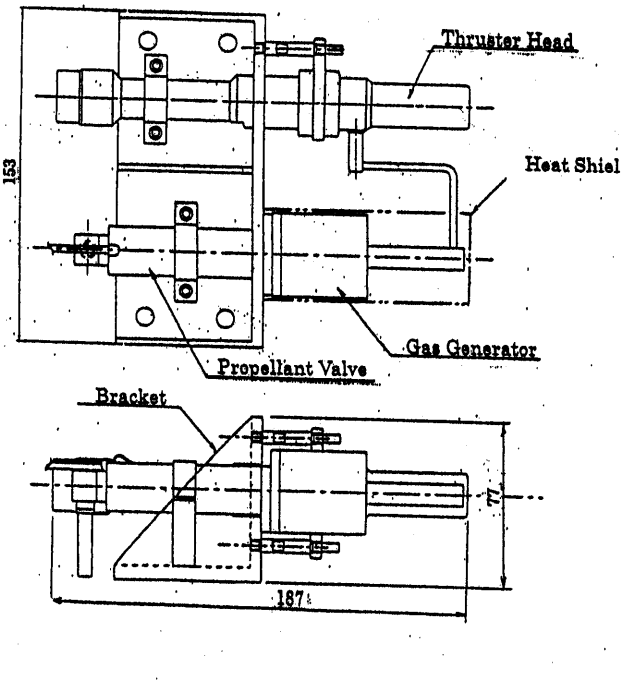


Fig.1 Configuration of 1kW DC Arcjet Thruster

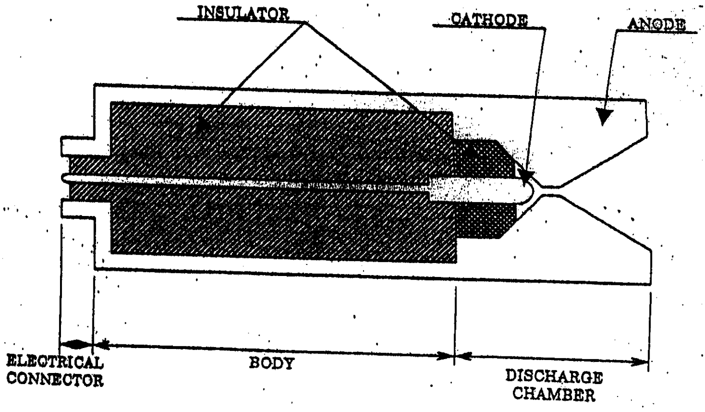


Fig.2 Conceptual structure of thruster head

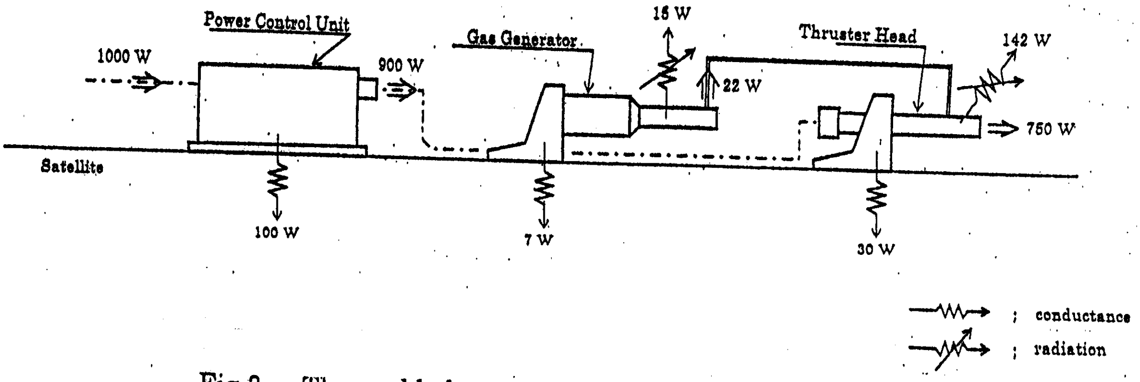


Fig.3 Thermal balance of 1kW DC Arcjet System

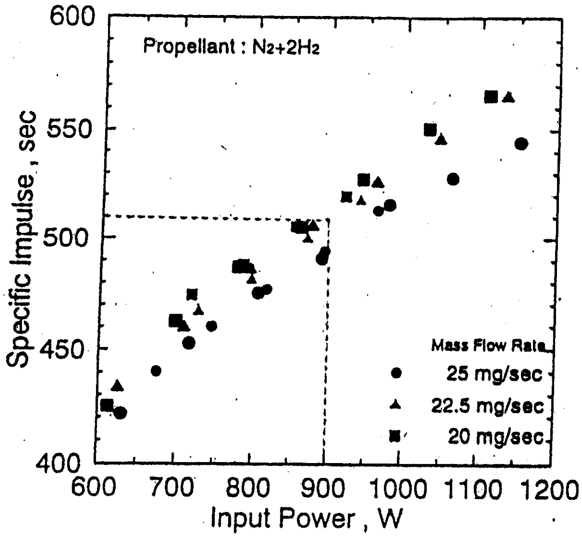


Fig.4 Thrust Performance

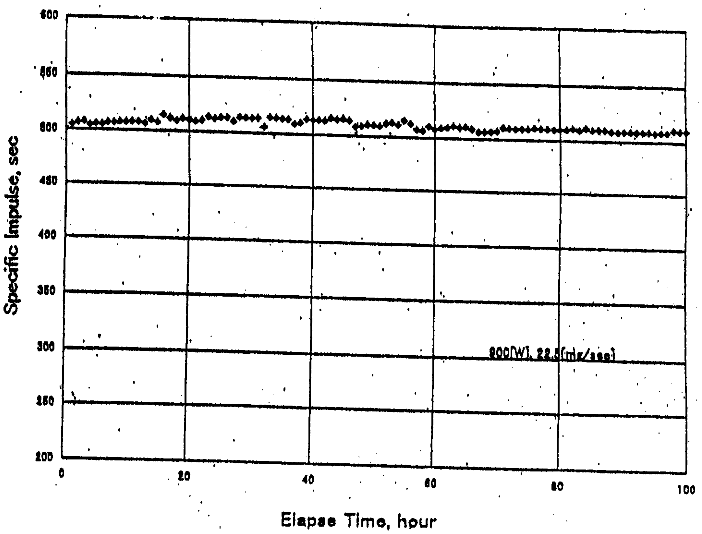


Fig.5 Thrust performance during 100 hr firing

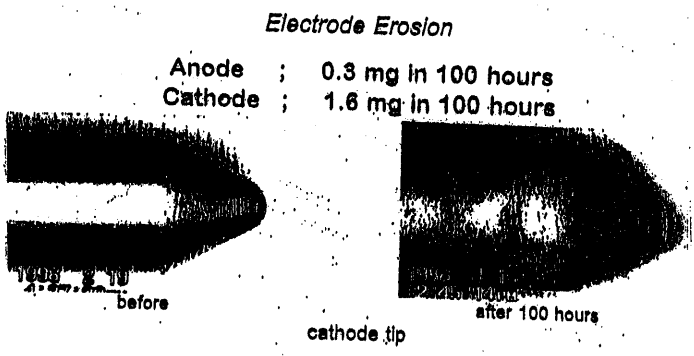


Fig.6 Electrode erosion through 100 hr firing

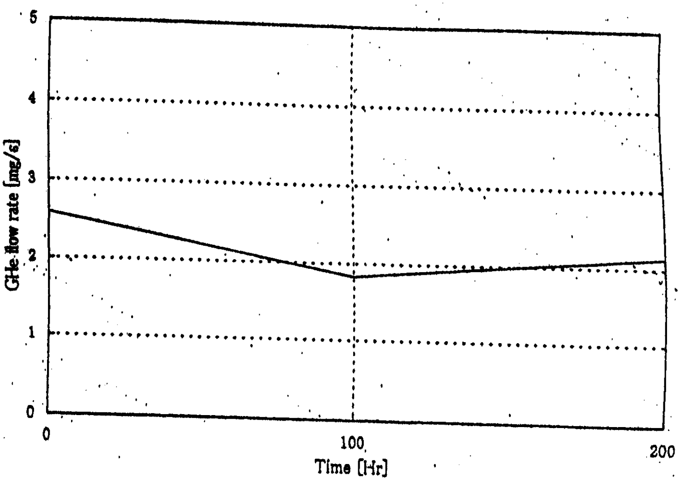


Fig.7 Gas flow rate characteristics during 200 hr firing