Performance Data Comparison of the Inert Gas RIT 10

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The radio-frequency (rf) ion thruster RIT 10, using mercury as propellant, has been developed for north-south stationkeeping of communication satellites. For that reason, the applicability of RIT 10 is questioned due to the toxicity and some other negative properties of mercury. The goal of the reported tests is to study in what respects the RIT 10 system could be operated using inert gases as propellants instead of mercury. Xenon, krypton, and argon have been selected as alternative propellants. After the feed line of the RIT 10 has been modified, the complete performance data have been measured for three inert gases. The tests demonstrate that mercury is interchangeable with xenon, losing only a few percent efficiency. Operation of the RIT 10 system with krypton or argon results in rather low efficiencies; and adaption of the RIT system to these propellants is necessary.

Nomenclature

e_0 = elementary charge
I_B = beam current
I_{ex} = extractable ion current
I_0 = neutral losses
P_{acc} = accelerator drain power
P_B = beam power
P_D = discharge power
P_N = neutralizer power
P_{rf} = rf power
P_T = thruster input power
ΔU_p = plasma potential
W_D = ion generation energy
η_d = beam divergence
η_e = electric efficiency
η_h = beam homogeneity
η_m = mass utilization
η_{tot} = total efficiency

Introduction

RESEARCH and development work on rf ion thrusters has been carried out for nearly twenty years at the University of Giessen. Emphasis has been made on the 10 cm ionizer diameter thruster, RIT 10, that uses mercury as propellant. This type of thruster reached laboratory maturity in 1969. Two years later, an industrial redesign took place including the development of the automatic power conditioning unit and the tank system. Preliminary tests in 1978 and 1979 at the Deutsche Forschungs- und Versuchsanstalt fuer Luft- und Raumfahrt (DFVLR), Stuttgart, West Germany have demonstrated a lifetime of more than 8000 h. Consequently, a qualification program has been started including environmental, functional, and compatibility tests at the DFVLR. In 1981, the RIT 10 was qualified for space application on the German TV Satellite as north-south stationkeeping thruster. For financial reasons, however, the first space application of the RIT system has been cancelled this year.[1-3]

Other applications of the RIT 10 in space seem to be hindered by the use of mercury as propellant. Despite the fact that mercury is an excellent propellant for ion thrusters, it has some drawbacks. Mercury is poisonous and, therefore, will not be allowed on retrievable systems or platforms that will be launched by the Space Shuttle Transportation System. Besides this, a property of mercury is the amalgamation of many metals. Coupled with the fact that mercury is liquid under normal conditions, possible users of electric propulsion fear a contamination of the satellite and a chemical reaction with the thruster's exhaust. A further argument against the use of mercury is the limited amount of mercury deposits on the Earth. This argument is not valid at the moment, but it will be if electric propulsion becomes a tool for stabilization of large structures in space or main propulsion of interplanetary probes. For these tasks, large thrusters will be necessary, and the mercury deposits would be rapidly exhausted.

For all these reasons, it seems advantageous to seek alternative propellants in order to secure an application of the RIT 10. The inert gases are well suited as propellants since they are non-toxic, do not react with any other material, and are gaseous (except at extremely low temperatures) so the thruster exhaust will not contaminate the satellite surface. The availability of inert gases depends strongly on the kind of gas. We decided in favor of xenon, krypton, and argon. Xenon is the most similar to mercury in performance on all accounts, but is the rarest. Argon is contained in the atmosphere at

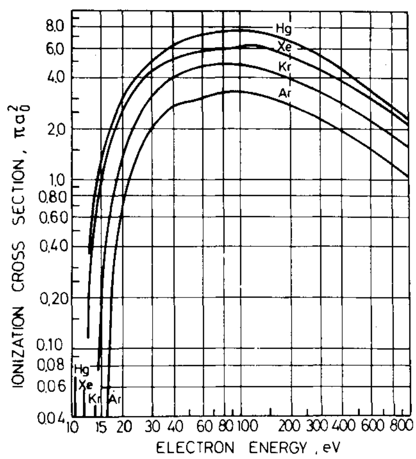

Fig. 1 Ionization cross-sections as function of the electron energy.

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nearly 1%, but its ionization conditions differ distinctly from those of mercury. Between both, krypton may be a compromise; therefore, it too has been taken into account. In Table 1 some important atomic data of xenon, krypton, argon, and mercury are listed, including the occurrence of inert gases in the atmosphere. The different ionization cross-sections in Fig. 1 indicate worse ionization conditions going from mercury to argon.[4]

In the following, the test arrangements will be described briefly including the reconstructed ion thruster test facility and the modifications of the RIT 10 for use of gaseous propellants. The basic performance data and the performance diagrams, calculated from the performance data, will be discussed and compared.

Performance Mapping

Test Arrangement

The tests have been carried out in the ion thruster test facility P 4000 Q, whose cross-section is shown in Fig. 2. A gate valve separates the lower main chamber from the upper thruster chamber. The main chamber, equipped with two mercury diffusion pumps, contains a frozen mercury pool as beam target and provides a vacuum in the low 10^{-6} mbar range. The ion thruster in the separated chamber has easy access for modifications or repair while the main chamber remains under vacuum and the pool may be kept frozen. The ion thruster is mounted vertically at the upper plate of the small chamber which also bears the electrical feedthroughs and a feedthrough of the propellant supply.

For the tests, an RIT 10 of the prototype level manufactured some years ago was placed at our disposal. In order to check the interchangeability of propellants with the RIT system, only modifications absolutely necessary for gaseous propellants have been made. The actual setup is sketched in Fig. 3. Only a modification of the feedline, essential to gaseous propellants, was made. The mercury vaporizer was replaced by a specially shaped joint connecting the insulator and the feedline. The gas taken out from a high pressure supply passed a pressure reduction valve and an electromagnetic control valve and was fed through the insulator into the ionizer. The control valve allowed any required pressure in the discharge vessel.

In addition, an ionization gage was mounted at the ceiling of the discharge chamber. That was not necessary for inert gas operation, but it enabled an easy monitoring of the discharge pressure. Moreover, it was now possible to feed back the pressure signal to the control unit of the electromagnetic valve and, thus, the discharge pressure can be kept constant at any value.

Finally, the original rf generator of MBB was replaced by a self-developed, water-cooled power amplifier. The only reason for this action was the fact that this system allows one to determine the power dissipation of the transistors by the temperature increase of the cooling water. The difference between DC input power and the dissipation is the rf output power of the generator that is an important parameter of the rf ion thruster.

The extraction voltage of 3 kV was split into a positive and a negative voltage of 1.5 kV each, as is done usually. Due to the intention of the tests, the extraction voltage was kept constant for all propellants. Also, the generator frequency was constant at 2 MHz during the tests.

Normally, the plasma bridge neutralizer is part of the ion thruster system. However, a neutralizer of prototype level was not available and experiments on this subject will not be reported in this paper. The reader must be referred to earlier studies with a laboratory neutralizer which proved the operation of the neutralizer DC-discharge with inert gases.[5] Tests with a life test model of EM status are planned at the end of this year using xenon as propellant.

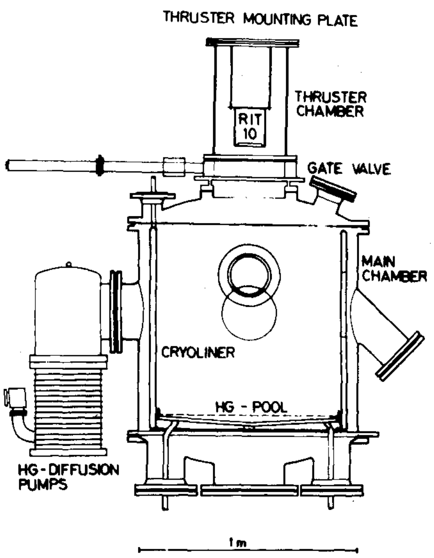

Fig. 2 Cross-section of the test facility P 4000 Q.

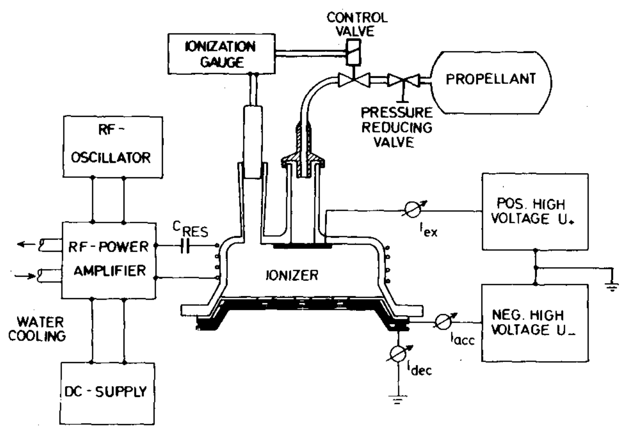

Fig. 3 Sketch of RIT 10 with propellant and power supply.

Table 1 Comparison of important atomic data

Property	Xenon	Krypton	Argon	Mercury
Atomic number	54	36	18	80
Mass number	131.3	83.8	40	200.5
Density, kg/m^3	5.9	3.7	1.8	13500
First ionization potential, V	12.1	13.9	15.7	10.4
Optimum electron engery, eV	120	80	90	100
Maximum ionization cross-section, 10^{-20} m^2	5.4	4.4	2.6	7.0
Second ionization potential, V	21.2	24.3	27.6	18.5
Occurrence in the atmosphere, vol.%	0.000008	0.0001	0.93	–
Reduction of thrust, %	20	37	55	0

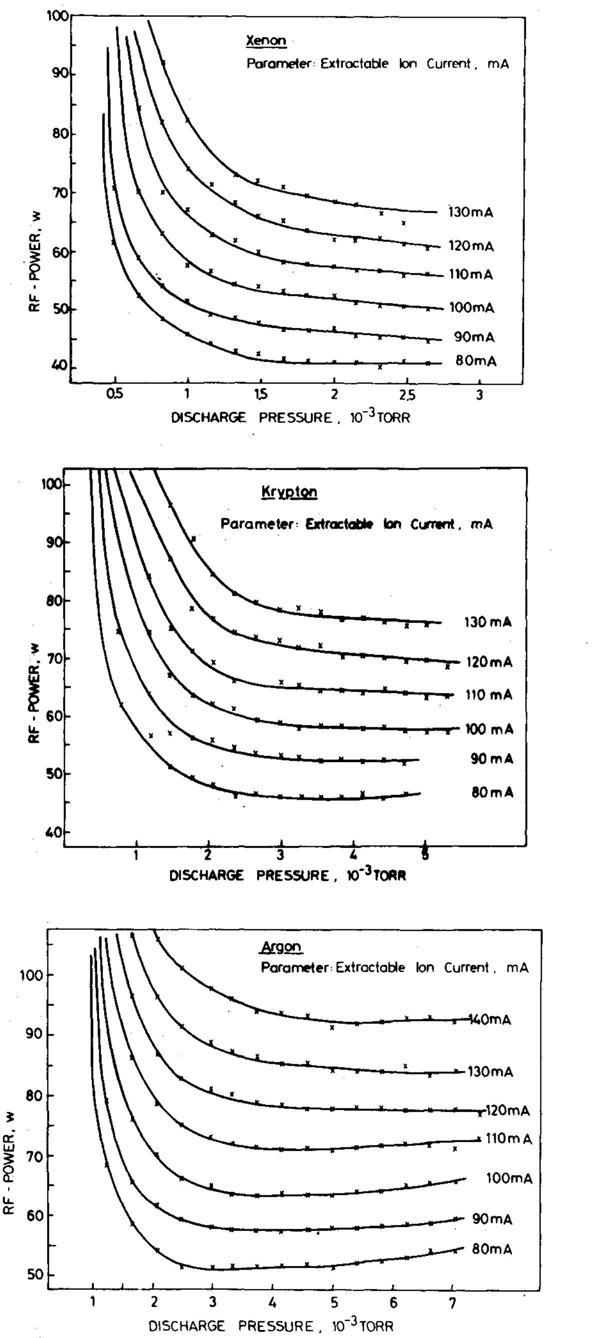

Fig. 4 Rf discharge power as function of the discharge pressure for different extractable ion currents.

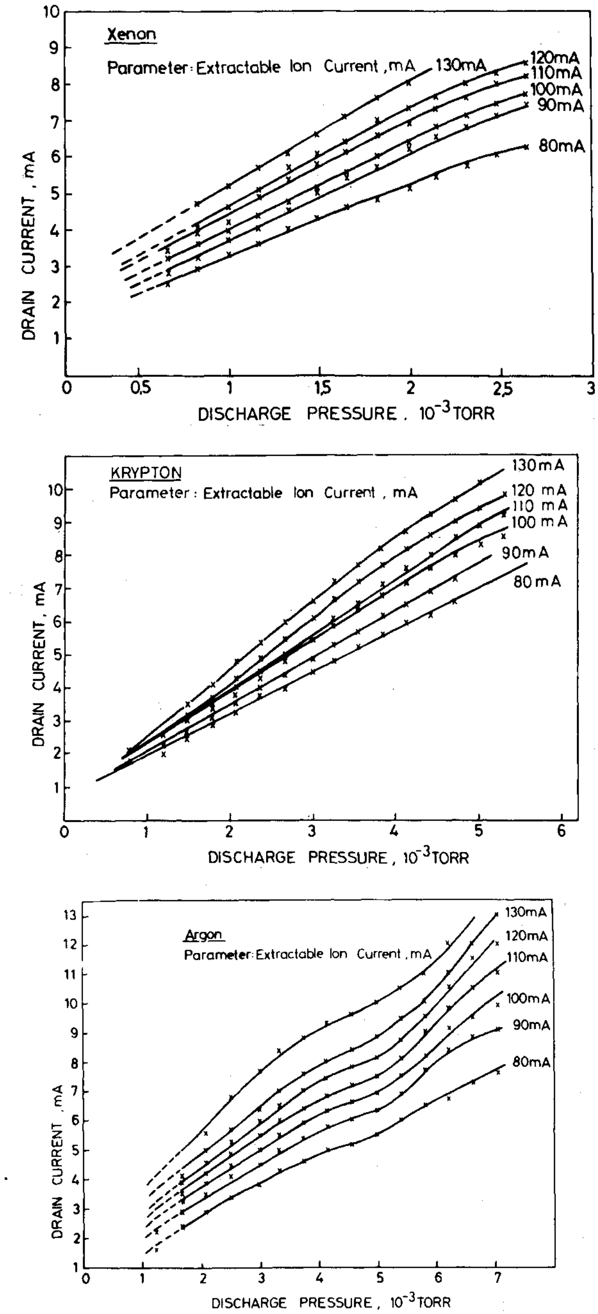

Fig. 5 Drain current as function of the discharge pressure for different extractable ion currents.

Measurements

The properties of rf plasmas are determined by the discharge pressure and the rf power coupled into the plasma. Along with the extraction voltage, the characteristics of an ion thruster are stipulated at given geometrical dimensions.

In order to obtain the basic diagram of the rf thruster, the discharge pressure was varied in discrete steps at fixed extraction voltage. At each pressure, the rf power was set to obtain different extractable ion currents from 80 mA in steps of 10 mA. Due to the change of the plasma density at different rf power, the rf generator output circuit was matched slightly according to the different conditions.

The basic diagrams in Fig. 4 demonstrate the dependence of the rf power from the discharge pressure for extractable ion currents from 80 mA to 140 mA. The well-known power-pressure relation is achieved, but in contrast to mercury no distinct minimum of rf power consumption (optimum discharge pressure) has been found except for 80 mA extractable ion currents. The worse ionization conditions of the inert gases are reflected directly in these diagrams by higher rf power levels for an equal ion current and by much higher discharge pressures in the 10^{-3} mbar range which are necessary to strike and to sustain the rf discharge.

A further important criterion for the quality of an ion thruster is the drain current to the accel-electrode. The drain current that is depicted in Fig. 5 as a function of the discharge pressure consists of two parts. Firstly, direct ion impact contributes to the drain current caused by defocused ions or misalignment of the grid system. Secondly, ions are generated within or behind the extraction system by charge exchange. The production rate of charge exchange ions increases with the number of neutral atoms, or, say, the discharge pressure, and the ion beam current as demonstrated in Fig. 5. The extrapolation of the curves at zero pressure gives that part of

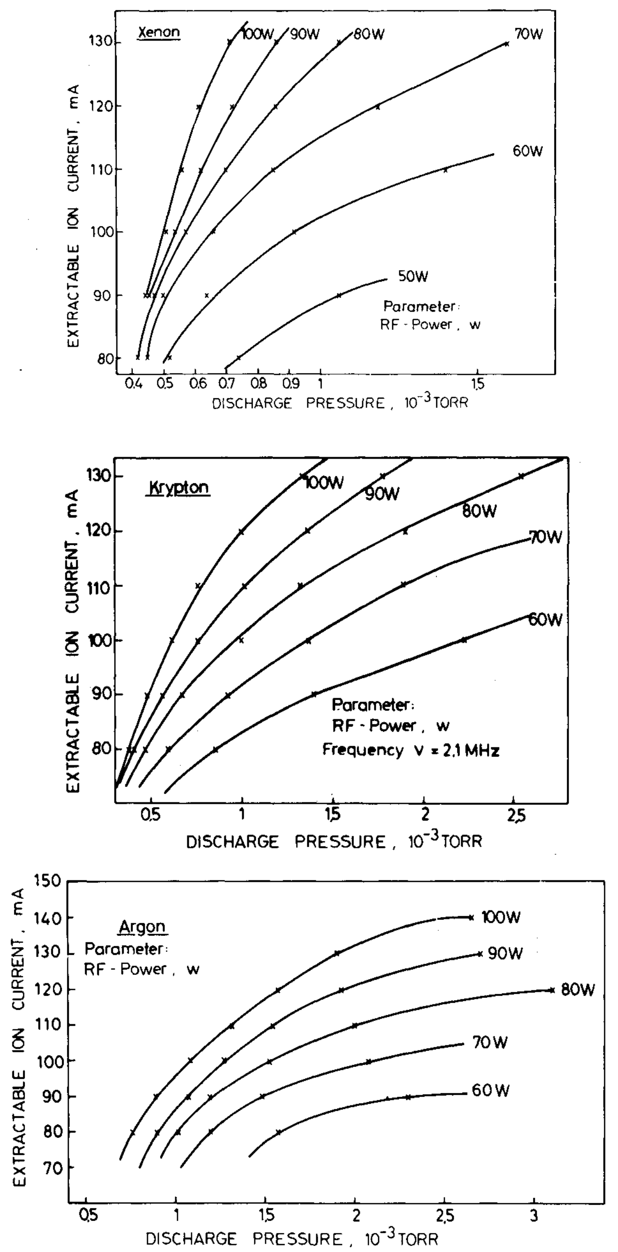

Fig. 6 Extractable ion current vs discharge pressure for different discharge powers.

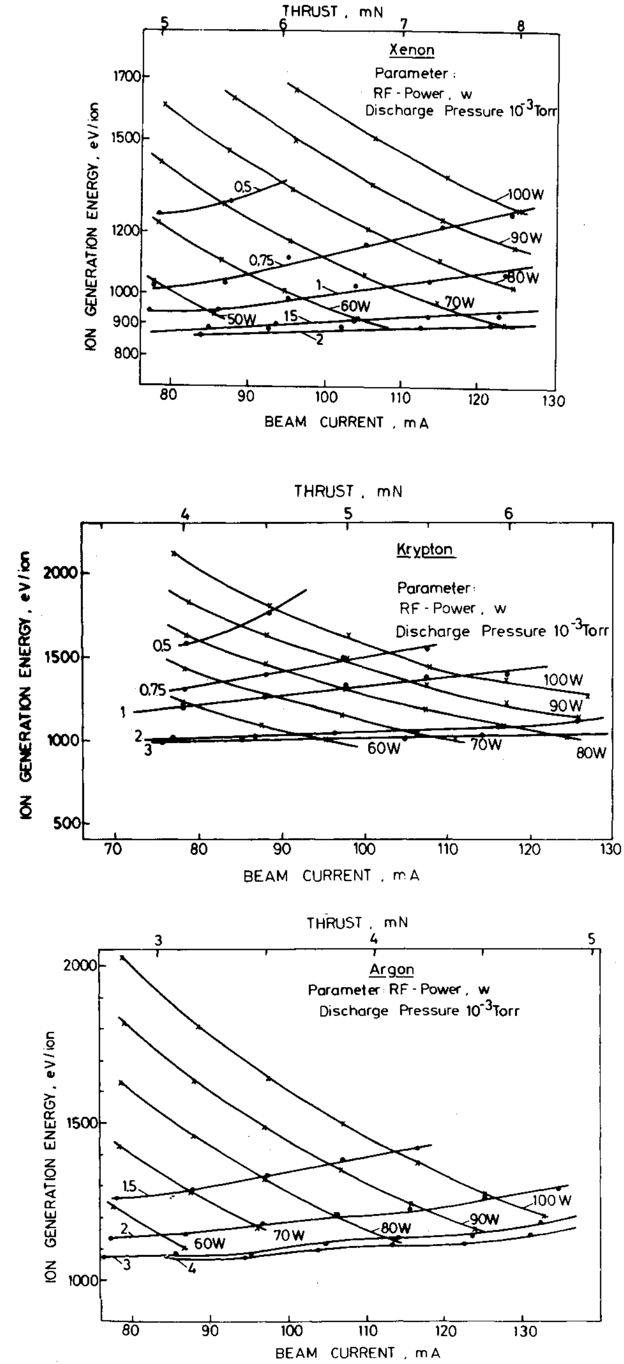

Fig. 7 eV/ion rates as function of the beam current for different power levels and discharge pressures.

the drain current caused by ion-optical reasons, since charge exchange ions are now eliminated. The drain current is relatively high according to the inexact alignment of the extraction system of the prototype thrusters. The deviations for different gases are caused by grid alignment that could have varied.

By exchanging the parameter extractable ion current with the rf power, one achieves the diagrams shown in Fig. 6 where the ion current is now graphed vs the discharge pressure. It is easy to recognize that the extractable ion current runs nearly into a saturation for argon. Higher ion currents can be realized by increasing the rf power but, again, no distinct pressure exists to determine a working point.

Performance Diagrams

From the basic ion thruster data of the chapter before, the further performance data are calculated. An important criterion of an ion thruster is the ion generation energy that means the discharge power that is necessary to produce a beam ion. The ion production costs W_D can be calculated from the equation

$$W_D = e_0 \cdot \frac{P_{rf}}{I_B} \tag{1}$$

with P_{rf} = rf power, I_B = beam current, and e_0 = elementary charge. The result for xenon, krypton, and argon is shown in Fig. 7 where the ion generation energy is graphed vs the beam current with the discharge power and discharge pressure as parameters.

Again, there is no minimum, and the ion generation energy is more or less constant at high discharge pressure for all beam currents. Since the ionization of inert gases requires more energy than that of mercury, we find increased eV/ion-rates. They range from nearly 900 eV/ion of xenon up to

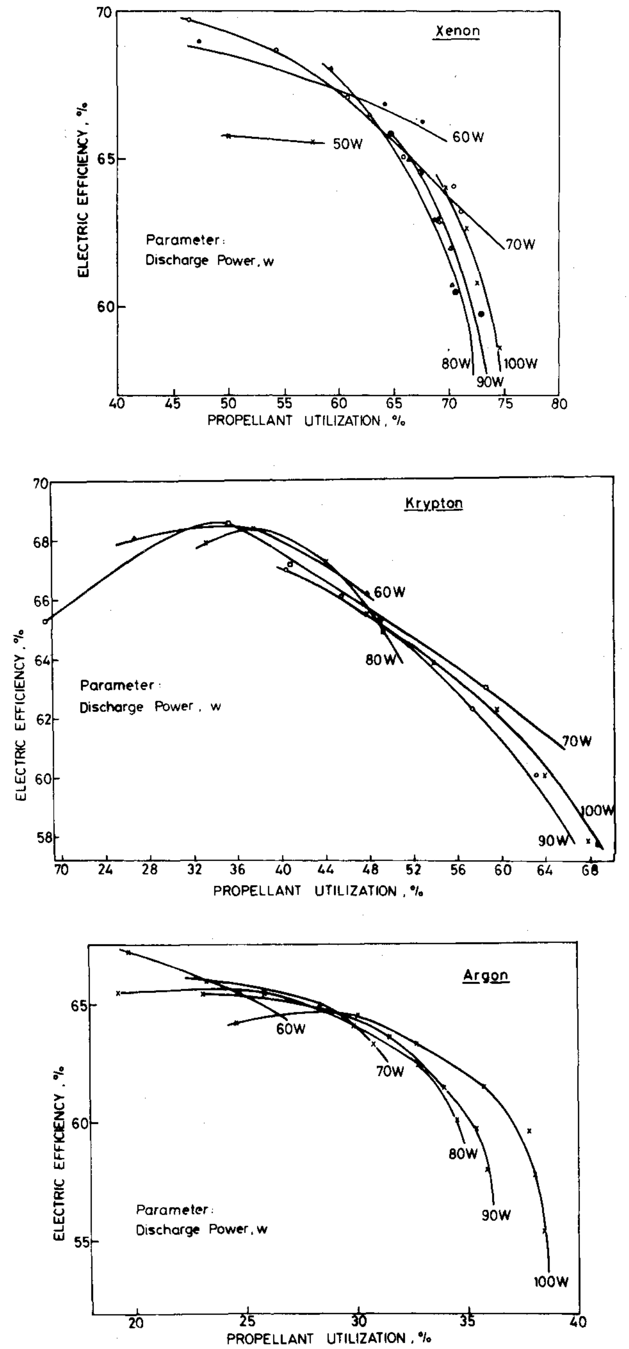

Fig. 8 The influence of the discharge power on the RIT 10-efficiencies for different gases.

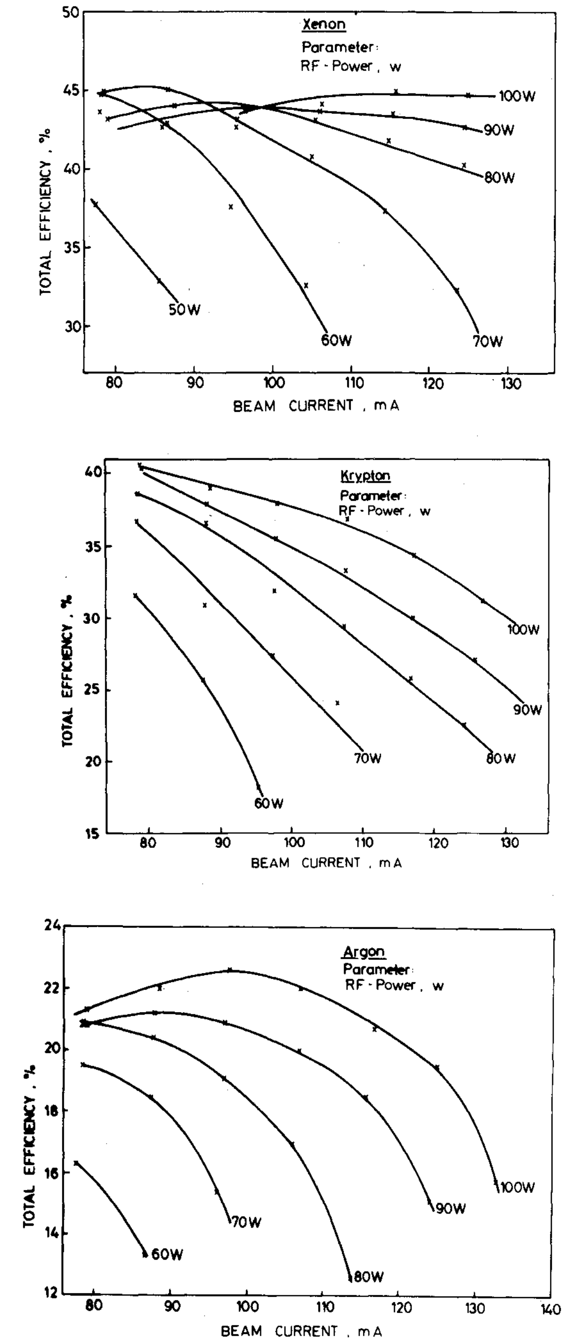

Fig. 9 Total efficiency as function of the ion beam current for different gases.

about 1100 eV/ion of argon and are higher than the 600 eV/ion for mercury.

As to be expected, the efficiencies show the corresponding trend. The electric efficiency η_e is given by:

$$\eta_e = \frac{P_B}{P_T} = \frac{P_B}{P_B + P_D + P_{acc} + P_N - \Delta U_p \cdot I_{ex}} \tag{2}$$

that means beam power P_B divided by the thruster input power P_T. P_D stands for the discharge power which generates the plasma, P_{acc} gives the accelerator drain power, and $\Delta U_p \cdot I_{ex}$ is part of the beam power coming from the potential difference between plasma and extracting anode and is delivered by the rf generator. The neutralizer power P_N has been neglected in this calculation since exact data are not available. Besides, the amount of 10 - 15 W for the neutralizer is small, compared with beam plus discharge power of about 300 W. The mass utilization η_m has been calculated from

$$\eta_m = \frac{I_B}{I_B + I_0} \tag{3}$$

with beam current I_B and the neutral losses I_0 which have been obtained using Knudsen's formula and putting in the measured discharge pressure, the gas data, and the geometrical dimensions of the extraction grids.

In Fig. 8 the electrical efficiency is graphed as a function of the mass efficiency for xenon, krypton, and argon. In principle, the efficiencies run vice versa as demonstrated here. The higher the electrical efficiency is, the lower is the mass efficiency, and vice versa. While the electrical efficiency is acceptable in the range of 60 to 70%, the worse ionization

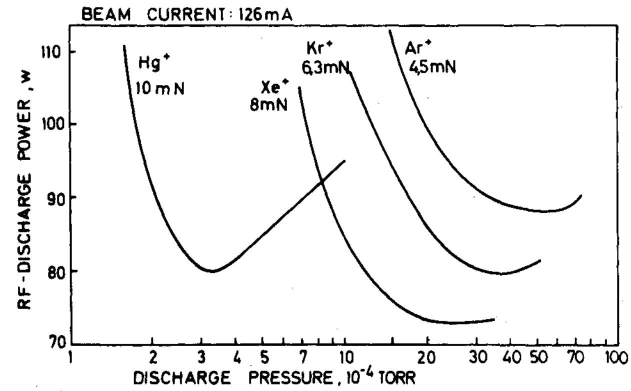

Fig. 10 Comparison of mercury and inert gas power to pressure relation at constant beam current.

conditions of inert gases are expressed by a low-mass utilization according to relative high discharge pressures. Except for xenon with 50 to 75%, the mass efficiencies of krypton and especially of argon are rather low and require improvements of the ion source.

In order to evaluate the thruster performance data, it is better to look for the total efficiency η_{tot} that is given by:

$$\eta_{tot} = \eta_e \cdot \eta_h \cdot \eta_d \tag{4}$$

with η_h for beam homogeneity and η_d for the beam divergence. The product $\eta_h \cdot \eta_d$ is assumed to 0.98 for the RIT 10 thruster. Figure 9 demonstrates the course of the total thruster efficiency as a function of the ion beam current with the rf power as parameter. Using xenon as propellant, we obtain a total efficiency of about 45% for ion beam currents from 80 mA to 130 mA. Looking at krypton and argon, we ascertain lower efficiencies, in general going down to only 23% for argon. Moreover, the efficiency decreases with increasing ion beam current due to the high discharge pressure, and with that, the neutral losses increase.

A direct comparison enables the diagram in Fig. 10 showing the rf power—discharge-pressure relation for one ion beam current or thrust level, respectively. Besides the loss of thrust, one can recognize that the plots of the inert gases are shifted in direction to higher discharge pressure and to higher rf power levels. The thrust delivered by argon is less than the half that of mercury but this may be compensated by changing the extraction parameters, as there are the ion beam current and the extraction voltage.

Conclusions

The experiments with the RIT 10 ion thruster using inert gases as propellant have proved the applicability of these propellants of rf thrusters. The tests with xenon were successful, demonstrating that mercury and xenon are interchangeable propellants since the obtained performance data are similar to both. Only the feedline of the thruster and, of course, the propellant storage tank must be modified in an appropriate way. Therefore, xenon is offered as an alternative propellant instead of mercury.

However, xenon is a very scarce inert gas and very expensive. Taking argon into consideration, we have found a reduction of the thrust and a distinct increase of the ion generation energy and the neutral losses. That means if argon, which is very cheap and comprises 1% of the atmosphere, should be used as a propellant,the RIT 10 ion thruster must be adapted to this gas. The same statement is valid for krypton as propellant.

If the gases should be used in the rf thruster, the ion source itself must be improved; the dimensions must be adapted to the ionization conditions. By this action it should be possible to realize lower ion generation energies and mainly lower neutral losses. The optimum extraction voltage must be checked with argon and perhaps slight corrections of the dimensions may result in a further improvement of the thruster efficiency.

Besides, the rf power needed to generate the plasma can be reduced by shielding the rf coil and discharge vessel with ferrite. By this technique the losses in metallic thruster components are reduced, as well as the losses in the rf coil and the rf generator.[6]

The preceding shows the interchangeability of mercury and xenon. The application of krypton or argon requires the above-mentioned improvements in order to obtain performance data that are comparable with xenon.

Acknowledgment

This paper is based on the diploma thesis of co-author H. Velten, who has carried out the experiments.

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