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FOREWORD

This report is submitted in fulfillment of the requirements of Contract AF49(638)-351, the experimental ion rocket program being conducted by Rocketdyne, a Division of North American Aviation, Inc. The program is sponsored by Air Force Office of Scientific Research, Propulsion Research Division. This report was reviewed and approved by R. II. Boden, Program Engineer.

Principal technical contributors include: A. T. Forrester, R. C. Speiser, D. J. Kerrisk, T. A. Coultas, P. E. Schumacher, J. Hyman, M. L. Swift, and A. W. Deveraux. The Technical Editor was E. W. Cornell.

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ADSTRACT

The purpose of this program is to gain an understanding of basic electrical propulsion principles, propellant proporties, and ionization and acceleration techniques. Experimental studies were performed on contact ionization ion sources, ion acceleration, and ion beam neutralization. Small research-type devices were successfully operated in ion motor coufigurations to verify theoretical analysis and to integrate experimental tests on components. The report discusses two types of vacuum systems: a bell jar, and a small steel tank. The tank operation proved more versatile, and two working variations of the device were built and tested. Instrumentation, fabrication, and neutralization techniques are described, and future work is outlined.

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INTRODUCTION

During the contract year, effort was devoted exclusively to contact (surface) ionization sources utilizing cesium as an expellant. Analytical considerations indicated the suitability of this type of system for ion propulsion. Calculations of the interaction between ions and neutral atoms dictated that the cesium be delivered to the ionizer surface by diffusion through a porous material. The several ion devices utilized in the experimental program were of this type.

Delivery of cesium to an ionizer surface from the downstream side is not feasible because of the excessive scattering of the beam and the voltage breakdown problems that would occur due to the relatively high delivery pressure necessary. There would also be excessive loss of unionized propellant. Cesium delivery must therefore be from behind the ionizer. The requirement of very low neutral-to-ion efflux ratio from the ionizer de⁺ rmines the use of a very fine structure ionizer in the following manner:

Consider an ionizer having raised and recessed areas, the raised areas being closer to the accelerating electrode. The buildup of space charge would prevent the emission of ions from the recessed regions because the fields would not penetrate into these areas. These areas would then coniribute only neutral cesium atoms to the total efflux. Because these areas are upstream of the ion-emitting areas, the cesium concentration would be higher, and too high a percentage of un-ionized propellant would result.

In the case of delivery of centum by diffusion through a porous material, calculations were made of ion and neutral atom efflux rates. From data presented in Ref. 1 it has been determined that to prevent the excensive R-1763

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evaporation of noutrals from a tungsten ionizer, it is necessary to maintain the covorage of the surface to less than 4 percent of a complete monatomic layer. At temperatures of 1600 K, very large ion currents (80 wa/cm^2) can be obtained with a coverage of only 1/2 percent. The problem was attacked by calculating whether diffusion of cesium over the surface of the tungsten could deliver adequate cesium to the exposed surfaces from the deeper-lying surfaces if the coverage difference is only 3.5 percent.

The rate at which cesium will be delivered to the 1/2 percent covered area from the 4 percent covered area depends on the surface diffusion constant and on the geometric relationship of the two areas. A diffusion constant extrapolated to 1600 % from lower temperature values of Taylor and Langmuir (Rof. 1) for cesium and tungsten were used. It was further assumed (for simplicity) that the surface had the form of a checkerboard with red squares having 1/2 percent coverage and raised above the black squares (which had & percent coverage) by an amount equal to the side of a square. For this situation, the delivery of cesium at a rate adequate to provide 80 ma/cm² from the red squares requires that the square size be not more than 10⁻⁴ cm. If the assumed surface is regarded as an approximation to the surface of a porous material, 10⁻⁴ cm can be sneedfied as a maximum pore size and pore spacing. This size appears to be easily achievable with available techniques. Further calculations indicated that, for a 1/16 in. thickness, this pore size will provide an adequate throughput of cosium with a pressure difference of the order of 1 mm of morcury. To achieve this pressure, it viil be necessary to maintain the coolum reservoir at a temperature of 275 C. The average ion current density from the ionizer under those conditions would be 40 ma/cm2.

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Assuming that the porous ionizer radiates as a black body, the power required for the junizer heating was compared with power which must be used to eccelerate the ions. The black body radiation is actually an uppor limit to the power radiated because the emissivity of the surface must be less than unity, and because the accelerator will serve as a heat shield. This calculated less may well be as much as five times too high. At 1200 K, the black body radiation is 12 w/cm^2 . If we accelerate the available ion current (0.4 ma/cm²) through 15,000 v, 6 v/cm² is delivered to the beam. At higher temperatures, the situation becomes much more favorable. At 1500 K, black body radiation increases to 29 w/cm², but if the available ion current (28 ma/cm²) is accelerated through 15,000 v, the power into the ion beam is 420 w/cm².

Considerations of electron bombardment of the ionizer by electrons produced by photoelectric emission, thermionic emission, or high field effects at the accelerating electrode, indicated that these phenomena could be negligible.

Due to the low specific charge of cesium, direct electrostatic acceleration was found most suitable in the early experiments. This was later modified to an accelerate-decelerate system in anticipation of neutralization of the ion beam with electron emitters near the exit aperture. The accelerate-decelerate system prevents the beam neutralizing electrons from getting back to the ionizer and also allows somewhat higher space-charge, limited-current densities in the acceleration gap.

DISCUSSION

Initial experimentation was performed in a bell jar vacuum svet which performed satisfactorily for simple configurations at modernic voltages, but proved inconvenient for more advanced devices. In February 1959, tests were started in the more versatile 8-in. tank facisity and the tests have continued to the present.

BELL JAR OPEDATIONS

In the first surface ionization tests, cesium was diffused through a 1/8-in.-thick, 1/2-in.-dia, porcus graphite ionizor in the apparatus in Fig. 1 and 2. A porcus tongston ionizor was also used in this configuration. Representative data are presented in Fig. 3 and 4.

It may be noted that the reservoir temperatures recorded are much too low to provide sufficient cesium vapor pressure and flowrate to sustain the currents measured. The thermal isolution of the reservoir from the ionizer region was not adequate and the cesium was heated by radiation and conduction down the delivery tube heating the surface of the cesium in the reservoir. This was corrected in later tests by the inclusion of radiation shielding inside thinner-walted delivery tubes.

The shapes of the curves of Fig. 3 are as superited for space-chargelimited and temperature-limited operation. The current varies as $\sqrt{3/3}$ for high ionizer temperatures and low accelerating voltages. The gradual breaks in the curves to temperature-limited values are due to the fact that the current can be space charge limited in the center of the sperture and importure limited in the peripheral area. Since operation at higher temperatures was still partially space charge limited, it was decided to go to higher current density bandling capacity configurations.

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Figure 3. Costum Ion Current From Graphito Instaur

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Figure 4. Centum Ion Currents From Graphite and Tungsten Ionizaya R-1763

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Accordingly, a slit-shaped source 1/8 in. wide and 2 in. long utilizing a percus nickel ionizer was tested. Operation was not successful, and later examination disclosed that the perces had closed. Another nickel ionizer was tested with similar results. The reason for the loss of percently was not clear, and the use of nickel as an ionizer material was discontinued.

EIGHT-IN. TANK OPERATIONS

The vacuum tank is a stainless steel cylinder 8 in. in diameter and 2 ft long (Fig. 5 and 6). The tank is evacuated through a 4-in. gate valve and a liquid nitrogen cold trap region by a 300 liter/sec, three-stage fractionating, oil diffusion pump.

The diffusion pump has a vater-cooled baffle at its inlet and is backed by a 7-liter/sec, two-stage mechanical pump also used for roughing. The diffusion pump is water cooled and it has an auxiliary cooling coil on the boiler to alkow fast cooling on shutdown. Its speed drops to 100 liter/ sec at 10^{-6} sm lig. To provide for both monitoring of pressure and trouble shoeting, there are ion gages in the main tank and in the liquid nitrogen trap region.

Both end plates of the tank are removable, and ion sources and collectors are directly mounted on end plates which can then be attached as desired. In addition there are three, A-in.-dia ports for viewing or instrumentation. Two are at 90 deg and 6 in. from the ends of the tank, and the third is in the middle of the tank at a 45 deg angle. The tank is wrapped with cooling lines to increase its power handling capacity.

Experimentation was switched to the 8-in. tank as soon as it was operable. The first device operated was designated SAMAY (Fig. 7 and 8). It

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featured a 1/2-in.-wide by 2-in.-long graphite ionizer clamped to a molybdenum box with a platinum gasket. The heater was a 0.060-in-dia tungsten, hairpin filament mounted inside the box. A heater on the reservoir assembly and a squirt tube on the vaporizer block allowed temperature control of the cesium delivery pressure. The whole source was operated at high positive voltage and insulated by the use of a section of pyrex pipe as the mounting system.

The accelerate-decelerate configuration was used in this and succeeding runs. Several partially successful runs were made with ion currents up to 6.5 ma being measured at the collector. The graphite ionizer had to be replaced due to cracking of the graphite. This was attributed to an interstitial soaking up of the cesium by the graphite with consequent swelling and cracking. The use of graphite has, for the time being, been abandoned.

It was decided early that the temperature controlled cesims delivery system did not afford fine enough control, and a second device, designated O(a = a Q), was developed. CHARLIE featured a needle value in the cesium supply $1_{a \in S}$. With this source, a porcus tungsten ionizer was used, and because of fabrication difficulties, initial running was carried out with a circular geometry. The ionizer was 3/16 in. in diameter and welded into the end of a molybdonum tube with an external heater filament (Fig. 9 and 10).

The CHARLE unit provided data from several good tests. Some representative data is presented in Fig. 11 and 12. Figure 11 shows the variation of the collector and other currents will the potential of the ionizer-field shaping electrode assembly (Φ_p) . The accelerating electrode (Φ_N) was held at 2.8 by negative potential. Some of the total current from the ionizer was intercopted by the accelerating electrode and the ground electrode-the latter dropping to zoro as Φ_p was increased. The surrent intercepted by the accelerating electrode and the ground electrode by the accelerating electrode and the ground electrode, indicating accelerating electrode and the surrent intercepted by the

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optimum focusing at the point for the fixed Φ_N . By this type of test the focusing properties of the accelerate-decelerate system can be determined. Figure 12 shows the variation of the collected ion beam current with Φ_p with fixed ratios of Φ_N to Φ_p as parameters. This type of test also helps determine the properties of the accelerate-decelerate system.

The 4-ma currents obtained correspond to current densitites of 30 ma/cm^2 at an ionizer temperature of about 1500 K. This current density is several times that needed for efficient operation of ion motors at that temperature. The 12-kv net acceleration potential corresponds to an exit velocity of 1.3 x 10⁷ cm/sec giving a specific impulse of 13,000 sec.

Small biasing voltages on the collector caused large changes in the measured collector current as shown in Fig. 13. This is a photograph of an oscilloscope trate with current as ordinate and collector biasing voltage as abscissa. The current varied from 1.3 to 4 ma for a collector voltage variation from -10 to +10 v. It is clear that such small voltages cannot produce appreciable variations in the trajectories of 12-kv ions. The cause of these current variations has not been definitely assigned, but they may be due in part to secondary electron emission at the collector, and in part to the existence of slow electrons and ions throughout the volume traversed by the beam. These current variations emphasize tho necessity of auxiliary measurements on the beam, such as thrust or beam power measurements as discussed below.

Oscillations in the beam current were observed at frequencies around 100 kilocycles per second. The frequency suggested two possible mechanisms. It is the correct frequency for ion plasma escillations corresponding to the average density of ions between the source and the collector. The half period of the escillations also corresponds to the transit time of the fast ions. Some data on these escillations are presented in Fig. 14.

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The oscillations could be readily quenched by raising the negative voltage on the accelerating electrode, or by allowing the pressure in the chamber to rise. Under no conditions were oscillations observed at currents loss than 1.2 mm (corresponding to about 10 mm/cm² at the source).

It is important to investigate these oscillations thoroughly and to determine whether they are inherent in this type of ion motor operation or are initiated by the test facility. If they originate in the accelerate-decelerate region, for instance, then it would be necessary to determine their effect on the efficiency and lifetime of the motor. If they are due to a cavity resonance effect, depending on the tank dimensions or the collector location, then means of eliminating their effect on other data may be found. The determination of the source of the oscillations will be pursued concurrently with other tests in future runs. A grounded fine wire grid installed in front of the collector is expected to reduce the effect of the two current variations noted on other measurements.

EIGHT-IN. TANK INSTRUMENTATION

Reservoir temperatures were generally observed with iron/constantan thermocouples. Ionizer temperatures were measured with a platinum/platinumrhodium thermocouple or with an optical pyrometer where the view was unobstructed.

Measurements of the power in the beam were made by observing the temperature rise of water circulating at a measured flowrate through a copper cone in which the beam was collected (shown schematically in Fig. 2). These measurements, initially made with thermocouples, gave satisfactory check with zero bias² collector readings, but the indications were small and response times so long that precision was poor. A much lighter cone was constructed, and the thermocouples were replaced with resistance thermumeters so that high sensitivity and shorter response time are now

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available. Calibration proved the device to be adequately linear with a sensitivity of 1/2 w in the 0- to 100-w range and an accuracy of 1/2 percent of full range. The range can be extended by reducing the resistance thermometer bridge excitation current, or the sensitivity can be improved by raising the bridge current.

The collector shown in Fig. 15 and 16 was used to measure the thrust produced by the ion beams. It consists of a grooved graphite beam-collecting plate and a capacitive displacement transducer mounted by pendulum supports with magnetic damping. For a 4 ma, 12 kv ion beam, the thrust should be 160 micropounds--far above the 10- to 20-micropound noise background of the measurement system. The thrust measurement did indicate approximately this level, but varied erratically with current and voltage. Lack of reproducibility of these measurements is attributed primarily to the oscillations previously discussed and which were discovered subsequent to the last use of the thrust measuring device. For currents of the order of 1 ma, the collector occasionally showed deflections opposite to the direction expected. This was attributed to electrostatic effects expected to be eliminated by the inclusion of the fine grounded grid in front of the collector.

FABRICATION TECHNIQUES

A continuous problem has been the leakproof mounting of ionizers to the cesium delivery system in such a yeary that their percent was not affected. Graphite ionizers were nickel plated around their peripheries and brazed or welded into position, or, in the case of the SAMMY device, elamped in place with a platinum gasket. Nickel was beliare welded, and tungsten was beliare welded to melybdenum or brazed in with nickel. Currently, a spet-welding technique for mounting percest tungsten to melybdenum is being pursued.

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NEUTRALIZATION

Following the close of the period covered by this report but prior to its writing, the neutralization of an ion beam was successfully undertaken. Electrons were supplied by a thermionic omitter at the neutral electrodo. The collector current measurement dropped to zero while the calorimetric power measurement which had agreed with the un-neutralized ion current measurement remained unchanged. This meant that the correct ion current was still reaching the collector, because the power delivered by the electrons would be negligible compared to that of the 12 kv energy ions. This test was made at the end of a brief run which had to be torminated because of high voltage difficulties resulting from too-close spacing of the field shaping and accelerating electrodes. More thorough testing under stable operating conditions is scheduled in the immediate future.

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FUTURE WORK

During this period, it has been ascertained that current densities as large as 30 ma/cm² can be obtained at 1500 K from a porous tungsten ionizor. This is in accord with expectations, and is more than adequate for efficient ion motor operation. There has also been evidence that the simple expedient of appropriately positioning a thermionic electron emitter is adequate for neutralization.

Several important problems remain to be attacked. It must be ascertained that the efflux of neutral cesium is small, compared to the ion efflux. For this purpose, a hot wire detector will be used. This consists of a hot tungsten wire with a suitable collimation system directed toward the source, and it detects neutral cesium atoms by ionizing them and collecting the positive ions formed. Another plauned test is the comparison of the veight loss of the cesium reservoir with the total integrated current for an extended run.

Electrode geometry, beam focusing, and neutralization studies will continue with emphasis on extended and iterated ionizer configurations. Pabrication techniques are an important problem for the larger ionizers and are currently being pursued. The possibility of obtaining wire in the micron size range and of fabricating ionizers out of this wire, or of using finely stoked films of tungston, are under investigation.

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