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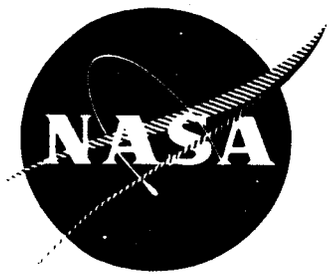

RESEARCH ON CHARGED COLLOID PROPULSION

by

S. P. Harris

prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Contract NAS 3-2597

Rocket Power, Inc.
a subsidiary of
Maremont Corporation
3016 E. Foothill Blvd.
Pasadena, California

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SUMMARY REPORT

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February 1, 1965

Contract NAS 3-2597

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SUMMARY

Using a cold cathode type ion source and a colloidal carbon feeding device, a beam of charged colloidal carbon particles was produced and measured. The beam was collected on a collecting electrode and at the same time a sample of the carbon particles striking the electrode was taken using a greased glass strip mounted on the collector to catch and hold the carbon particles. Photomicrographs of the carbon particles were taken. The average charge-to-mass ratio for the charged colloidal carbon beam was computed from current, time and mass measurements and a quadrupole mass spectrometer was also tried. Average charge-to-mass values showed considerable variation but were of the order of magnitude of 1000 coulombs/kilogram. Direct measurements of colloidal carbon beam thrust, using a ballistic pendulum, were made. This thrust was in the milligram range for a 3 μa charged colloidal carbon beam with approximately 2000 volts of energy. With a properly designed high current ion source and carbon feeder, it should be possible to increase the charged carbon beam to 1 ma and the energy to between 50 and 100 KV. This would increase the thrust by a factor of about 2000 to roughly 2 gm. or 4 millipounds.

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ABSTRACT

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A beam of charged colloidal carbon particles was produced and measured using a cold cathode type ion source and a colloidal carbon feeding device. The beam was collected on a collecting electrode. Photomicrographs of some of the carbon particles collected were taken. Average charge-to-mass ratios for the charged colloidal carbon were computed. They showed considerable variation but were the order of magnitude of 1000 coul/kgm. A very lightweight ballistic pendulum was used for beam thrust observation.

Author

I. Introduction

Previous publications[1-4] have discussed the possibilities of using charged colloidal particles for propulsion. A number of kinds of liquid droplets and colloidal solids such as mercury, mercurous chloride, glycerol, oil and colloidal carbon have been tried as propellants. This particular investigation used colloidal carbon as the propellant. Previous investigators in this laboratory[4] obtained information on the size and agglomeration properties of commercially available colloidal carbon and determined that it could be charged in an ion source.

The advantages of charged colloidal particles over ions for propulsion have been enumerated in many articles and reports. The most significant advantage is that with limited electrical power available a charged colloidal particle thrustor, generates higher thrust density than for atomic ions and can operate in the specific impulse range of 2000-5000 sec. at high efficiency.

This report describes research work designed to investigate the production and acceleration of charged colloidal particles, to measure some of their properties and to attempt to exploit them as a means of electrostatic propulsion.

The author would like to thank Dr. S. Singer, Mr. N. G. Kim, Mr. P. Leichner, and Dr. A. Holub for assistance in this project. He would also like to thank Mr. M. Farber for his interest in the work.

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1. Norgren, C. T. and Goldin, D. S. "Experimental Analysis of the Exhaust Beam from a Colloid Thrustor," NASA TM X 52035, AIA Paper 64-674, Philadelphia, Penn., Aug. 31 - Sept 2, 1964.

2. Mickelsen, W. R. "NASA Research on Heavy-Particle Electrostatic Thrustors" Paper 63-19, IAS Meeting, New York, N. Y. , Jan. 1963.

3. Singer, S. and Farber, M., "Electro-propulsion with Colloids, Astronautics, Jan. 1962, p. 34.

4. Singer, S. Kim, N. G. and Farber, M., "An Experimental Study of Colloidal Propulsion Using Sub-micron Solid Particles," AIAA Electric Propulsion, Conf., Mar. 11-13, 1963.

II. Description of Equipment

A vacuum system, consisting of a mechanical pump, a diffusion pump and sections of 6" diameter Pyrex glass pipe, was set up. A colloidal carbon feeder, a cold cathode ion source and a collecting electrode were installed in the vacuum system. A sketch of the system and its associated circuits is shown in Figure 1. The ion source consists of two copper cathode discs with a copper anode ring in between. An axial magnetic field of about 720 gauss is applied with a permanent magnet. The carbon feeder is of the screw type and feeds colloidal carbon into the anode ring . Details of the ion source are shown in Figure 2. A photograph of the ion source and carbon feeder is shown in Figure 3. The carbon feeder reservoir is continuously pumped with a vacuum pump.

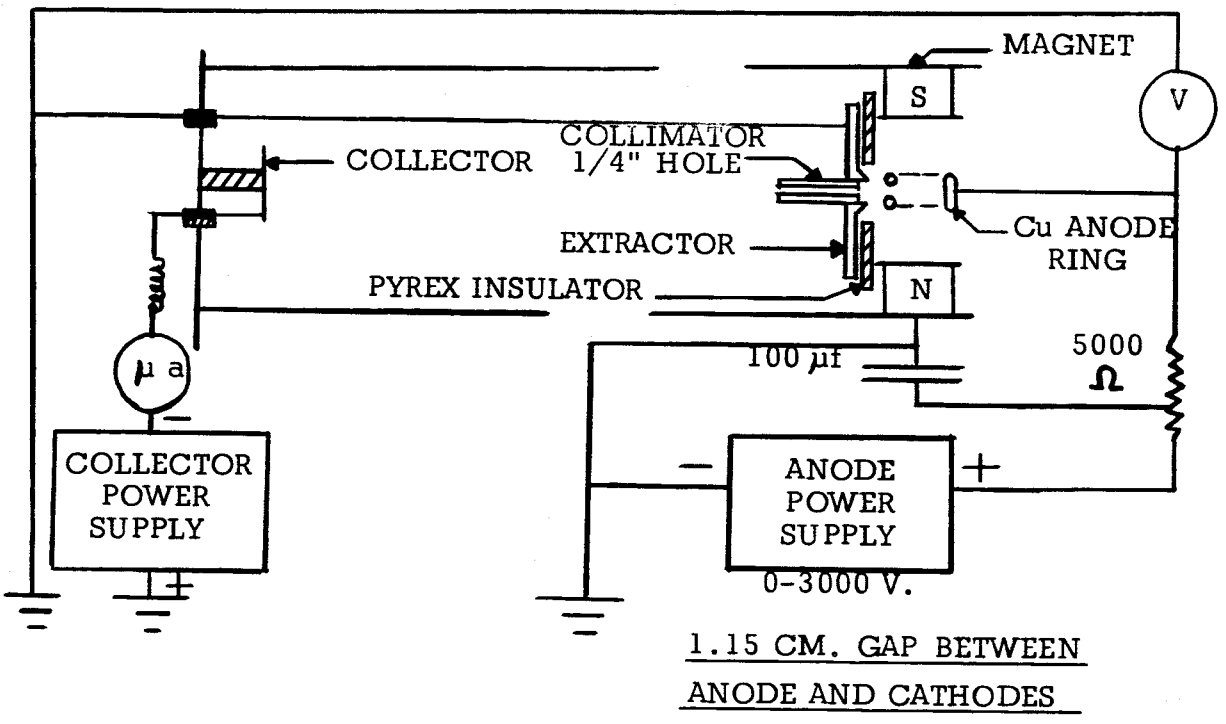


FIG. 1 SYSTEM AND CIRCUITS

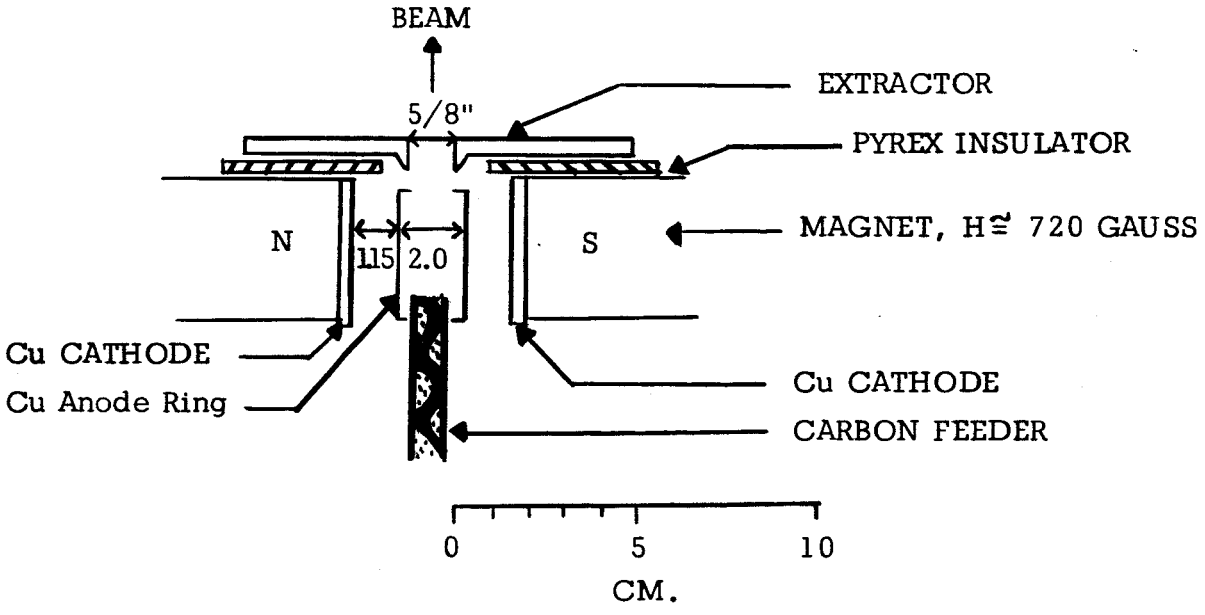


FIG. 2 ION SOURCE

Fig. 3 Ion Source with Carbon Feeder at Left

III. Experimental Data

In the earlier work this ion source was operated on residual gases, probably consisting of oxygen, nitrogen and diffusion pump oil vapor. With the following conditions an experiment was performed to measure the ion beam current and carbon beam current and to collect a sample of the charged colloidal carbon particles from the beam on a greased glass strip mounted on the collector electrode:

Length of run	12 min.
Ambient pressure	2 to 6.5 x 10^{-4} mm (residual gas)
Anode supply voltage	1350 to 2250 v.
Anode current	100 to 200 ma
Collector voltage	1000 v negative
Collector current	.02 to .04 ma*
Collector current before feeding carbon	.01 ma*
Extractor is at ground potential	
Distance from extractor to collector	22 inches
Extractor opening	5/8" diameter hole

Since the ion source was somewhat unstable in the above experiment, an accurate charged carbon beam current value was not obtained, but it was probably the order of microamperes. A very interesting effect was noticed in the manner in which carbon particles were deposited on the grease surface in streaks (see Figure 4). It is thought that these streaks are electrical leakage paths along which the relatively large amount of charge deposited by atomic ions is neutralized by electron flow from the collector electrode. Since these paths are at a more negative potential than the surrounding area they tend to attract the positively charged carbon particles. These streaks are not obtained when the ion beam is deflected with a large magnet so that the total current is small and not much electrical leakage is required.

*End plate of vacuum system was used as the collector this time.

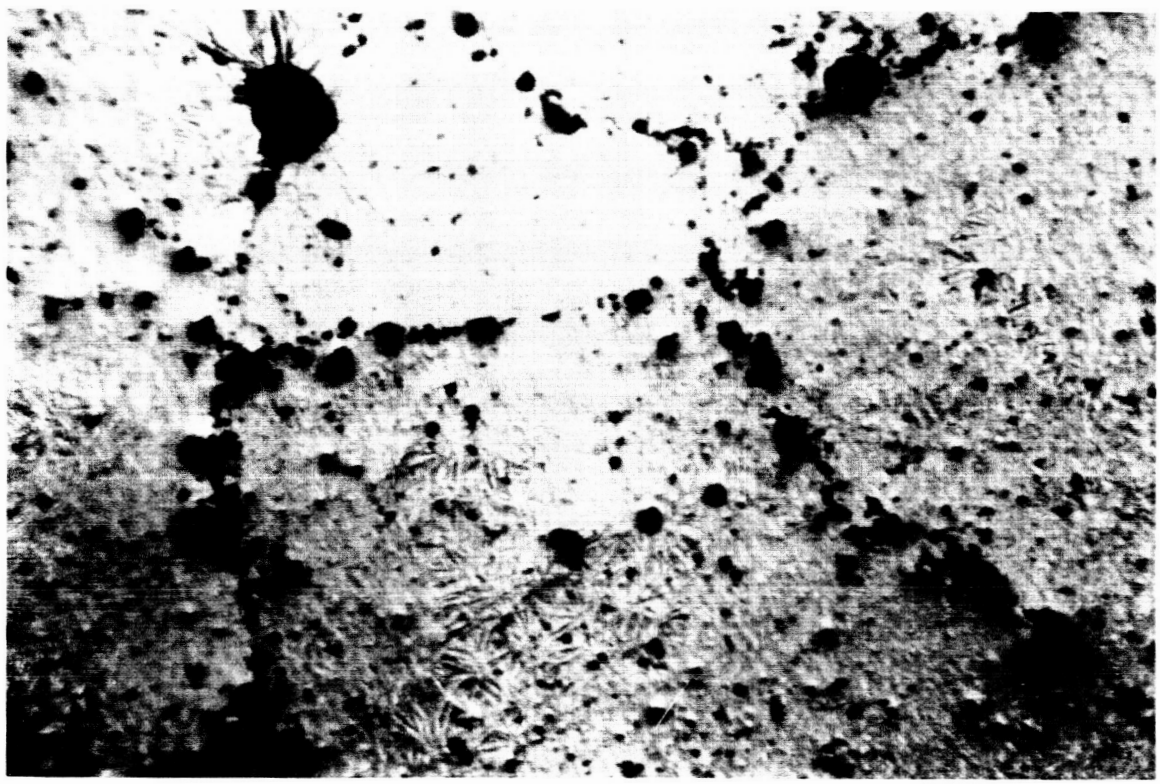


Fig. 4 - Photograph of Carbon Deposited on Greased Glass Strip, Showing Streaks, Magnification - 130X.

A later experiment to measure the charged colloidal carbon beam current was performed under better conditions. Argon gas was fed into the ion source. The ion source operated much more reliably on argon than on residual gases and the electrodes stayed cleaner. A large magnet was mounted outside the glass vacuum pipe between the extractor and the collector to deflect gaseous ions. It produced a field of about 860 gauss. The other operating conditions were as follows:

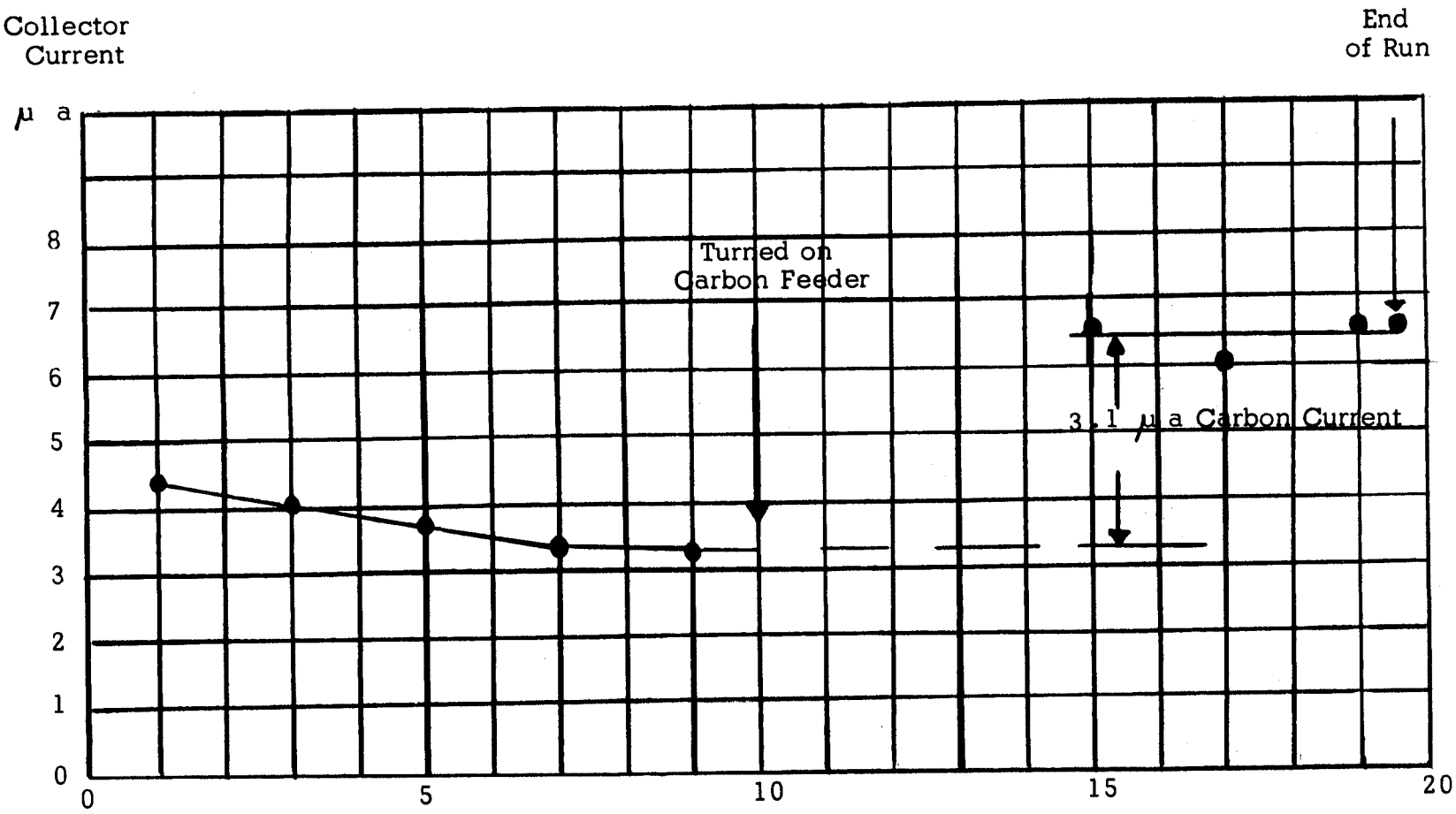
Length of run	8 min.
Ambient pressure	1.4 to 1.6 x 10^{-4} mm. (argon)
Anode supply voltage	2220 to 2500 V.
Anode current	90 to 105 ma
Collector voltage	500 v. negative
Collector current	6 to 7 μ a
Collector current before feeding carbon	3.3 μ a
Extractor at ground potential	(= 1900 to 2000 V below anode)
Distance from extractor to collector	21 inches
Extractor opening	5/8" diameter hole

A graph of the beam current vs. time for the above run is shown in Figure 5. After the carbon feeder was turned on an increase of 3.1 μ a was observed due to charged carbon. At the same time charged carbon particles were collected on the greased glass strip mounted on the collector disc. A heavy random deposit was obtained (see Figure 6). A calculation of the approximate average charge-to-mass ratio was made from this photograph and the data above. It is shown here.

$$\text{Charge collected} = 3.1 \times 10^{-6} \text{ amp.} \times 480 \text{ sec.} = 1.49 \times 10^{-3} \text{ coul.}$$

Measurement of the diameters of 10 particles or agglomerates at random on the picture gave an average diameter of 29 microns. We will use this as the average thickness of carbon on the collector, noting that the area is about 1/2 covered with carbon.

$$\text{Area of collector} = \frac{d^2}{4} = \frac{(5.71)^2}{4} = 25.4 \text{ cm}^2$$



TIME - MINUTES

Fig. 5

Beam Current vs. Time

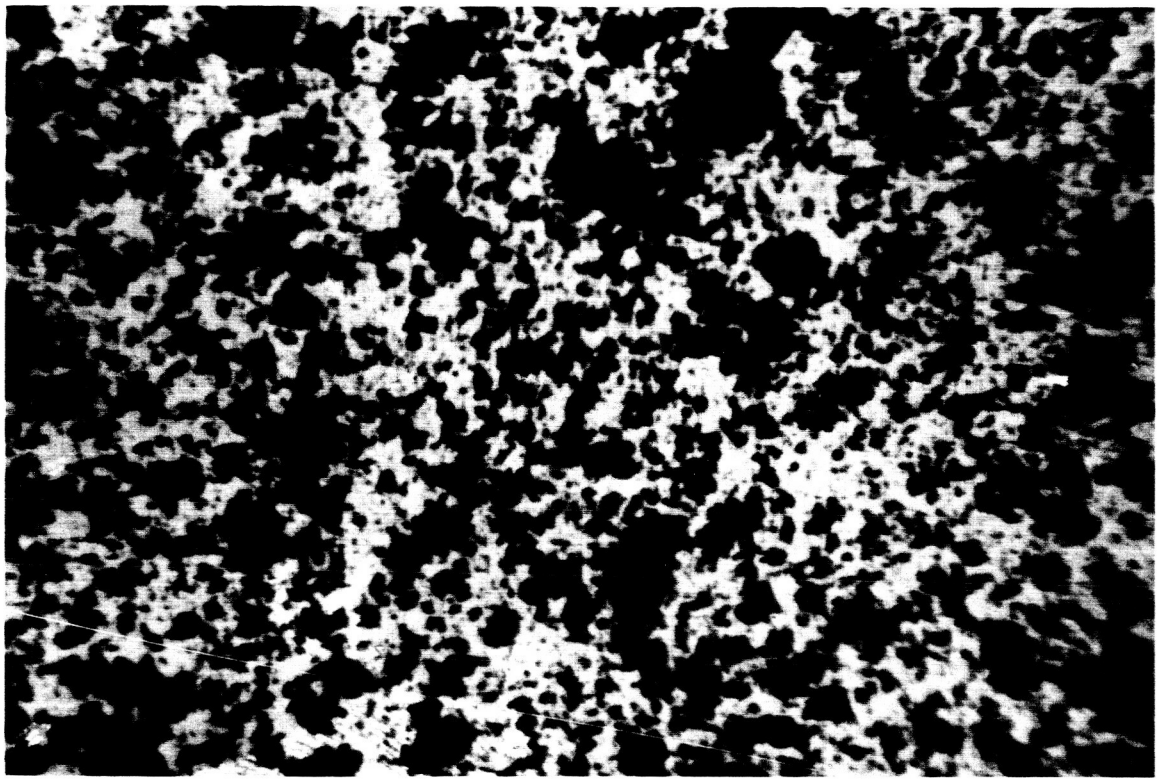


Fig. 6 - Photograph of Carbon Deposition on Greased Glass Strip, Magnification - 130X.

Vol. of carbon = 0.0029 x 1/2 x 25.4 = 0.037 cc

Using measured gross density of our carbon = 0.054 gm/cc. wgt. of carbon striking collector = 0.037 x 0.054 = 0.002 gm.

$$\frac{\text{charge}}{\text{mass}} = \frac{1.49 \times 10^{-3} \text{ coul.}}{0.002 \text{ gm.}} = 0.75 \text{ coul/gm}$$

$$\frac{\text{charge}}{\text{mass}} = 750 \text{ coul/kgm average}$$

The charge-to-mass ratio obtained by this technique is a very rough estimate.

IV. Discussion of Particle Charging Mechanisms

There are several possible mechanisms for positively charging colloidal particles in an ion source such as ours. One is secondary electron emission (emission of two or more electrons) when an electron is captured by a colloidal particle. Another is capture of positive ions by the colloidal particle. As the charge increases on the positive colloidal particle, the repulsive potential for positive ions becomes so large that no more positive ions have enough energy to reach the colloidal particle.

As an example, let us calculate the potential, V, acquired by a 4 μ diameter particle which is to be charged, we assume, to 1 coul/gm by positive ion attachment. For convenience we will assume a spherical particle.

$R = 2 \times 10^{-4}$ cm.

$4/3\ \pi R^3 = 4/3\ \pi\ (2 \times 10^{-4})^3 = 33.5 \times 10^{-12}$ cm^3

mass $= 0.054 \times 33.5 \times 10^{-12} = 1.8 \times 10^{-12}$ gm

$V = \frac{Q}{R}$ where Q is the total charge

$$V = \frac{1 \times 3 \times 10^9 \times 1.8 \times 10^{-12}}{2 \times 10^{-4}}$$

Q = coul/GM x Conversion Factor x Mass in GM. (1 coul/GM is the assumed charge-to-mass ratio. 3×10^9 is the conversion factor.)

$V = 27$ stat volts

$V = 8100$ volts

The effective mean density of colloidal carbon used in the above calculation is 0.054 gm/cc. Whether or not an ion of a given energy may reach a charged colloidal particle having a given charge-to-mass ratio depends also upon the size of the particle. The 4 μ diameter particle we have chosen could not be charged to 1 coul/gm by our source unless at least 8100 V. were applied. It is easier for the smaller particles to acquire more charge at a given charge-to-mass ratio because their potential is lower.

A third mechanism for charging is X-ray photoelectric effect and Compton effect. Many soft X-rays are produced in the ion source by bombardment of the anode with electrons. These X-rays have all energies up to the maximum electron energy which is the anode to cathode potential difference, and can produce photoelectrons of this energy. The positive charging of oil droplets of colloidal size by X-rays in vacuum is described by Millikan.[5]

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5. Millikan, R. A., "The Electron," p. 78-80, University of Chicago Press, 1924.

When colloidal carbon is fed into the ion source there is a definite effect on the operation of the ion source. The current between the anode and the cathode diminishes and the voltage goes up. In fact, if large amounts of carbon are fed in, the discharge can be quenched. These are recombination effects. The recombination of ions and electrons in vacuum is discussed in reference 6. In order for momentum to be conserved in this recombination process a third body is needed to absorb momentum. This body is usually the wall of the container. Thus, large surface area in an ion source gives a high recombination rate. Adding colloidal carbon, as we do, furnishes many third bodies and large surface area in the center of the discharge and, therefore, produces much recombination. The ion source anode current typically may fall from 115 ma to 90 ma after carbon is added.

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6. Millman and Seely, Electronics, p. 249-50, McGraw-Hill, 1951.

V. Quadrupole Measurements

Some attempts were made to measure e/m both for atomic ions of argon and for charged colloidal carbon particles using our two quadrupoles, one 1 foot long and the other 1 meter long. The method of use of quadrupoles as mass spectrometers is described in reference 7. The electrode spacing ($2 r_o$) for these two quadrupoles is the same, 3.8 cm. When measurements are made on charged colloidal particles a frequency of about 7 KC is imposed on the quadrupole and when atomic ions (such as A^+) are used a frequency of about 640 KC is used since the e/m values for ions are about 4 orders of magnitude higher than those for charged colloidal particles.

The relationship governing quadrupole operation is given in reference 7 and is as follows:

$V = KA \nu^2 r_o^2$ where

V is the applied A.C. voltage, peak to ground

K is a constant

A is the atomic weight (or equivalent amu/z)

ν is the frequency in megacycles/sec.

r_o is 1/2 the electrode spacing in cm.

Because of poor resolution with our quadrupoles, the results are rather limited. Collector current vs. A.C. peak voltage quadrupole data with colloidal carbon being fed into the ion source gave e/m values. If the maxima are used to calculate e/m ratios from the above equation, values of 2500 and 1200 coul/kgm are obtained. The possible error in these figures is, of course, large and the actual value of e/m for charged carbon particles is probably spread over a wide range of values.

VI. Ballistic Pendulum Thrust Measurements

An approximate calculation of the thrust generated by the charged colloidal carbon beam can be made using the data given on p. 8 and 11

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7. Paul, Reinhard and Von Zahn, "Das elektrische Massenfilter als Massenspektrometer and Isotopentrenner", Zeitschrift fur Physik, Vol. 152, p. 143 (1958).

$$\frac{\text{Mass}}{\text{Time}} = \frac{0.002 \text{ gm. carbon}}{480 \text{ sec.}} = 4.2 \times 10^{-6} \text{ gm/sec of carbon}$$

$$E/m = 1.46 \times 10^{10} \text{ ergs/gm}$$

$$\text{Thrust} = \sqrt{2 \left(\frac{dm}{dt}\right)^2 E/m}$$

Thrust = 0.0016 millipounds

In the above and on the next page,

E = energy of the carbon beam
m = mass of the carbon
V = accelerating voltage of the beam
e = charge carried by mass m of carbon
t = time

In view of the above calculation it was decided to make a direct measurement of the thrust produced by the charged colloidal carbon beam. A collecting electrode for measuring the thrust was fabricated of 1 mil aluminum foil in the form of a cone suspended with its axis parallel to the beam, by means of three 1 mil platinum-tungsten alloy wires, resulting in a ballistic pendulum of length 6.3 cm. The principle is the same as that of the ballistic pendulum reported by Byers, Kerslake and Grobman,[8] except that our first cone weighed only 110 mg and was very much more sensitive.

In the first experiment with this pendulum collector cone, the ion source was operated with argon being fed in and a large magnet was mounted outside the vacuum pipe so as to deflect atomic ions. A residual ion beam which the magnet did not remove completely amounted to 3.8 μ a and deflected the pendulum cone about 0.01 cm. When carbon was fed into the ion source the current in the beam increased to about 10 μ a and the cone deflected about 0.07 cm more. The cone motion was measured with a cathetometer and since there was some oscillation of the cone this introduced an error, perhaps as

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8. Byers, D. C., Kerslake, W. R., and Grobman, J., "Experimental Investigation of Heavy-Molecule Propellants in an Electron-Bombardment Thrustor", NASA TN D-2401, August 1964.

much as $\pm$ .03 cm in the deflection measurement. The thrust calculated from the above deflection was 1.2 mg.

After the experiment the collector cone was removed carefully and weighed on a microbalance. The carbon adhering to it was then brushed off and the cone was reweighed. The cone had gathered 0.815 mg of carbon from the beam in 10 minutes. Using the current, the time and the weight of carbon collected, we calculate an average e/m value.

$$e/m = \frac{600 \text{ sec.} \times 6.2 \times 10^{-6} \text{ amp}}{0.815 \times 10^{-6} \text{ kgm}}$$

$$e/m = 4500 \text{ coul/kgm}$$

This value may be somewhat high because of carbon which was collected by the metal support for the collector cone, which was at the same potential as the cone, and which was not included in the weight of carbon collected. This could lower the e/m value by a factor of about 2.

Using the above e/m value and the accelerating voltage of 1950 volts, a calculation of theoretical thrust on the cone is made.

$$E/m = Ve/m = 1950 \times 4.5 = 8.8 \times 10^{3} \text{ joules/gm}$$

$$E/m = 8.8 \times 10^{10} \text{ ergs/gm}$$

$$\frac{\text{mass}}{\text{time}} = \frac{.000815}{600} = 1.36 \times 10^{-6} \frac{\text{gm. carbon}}{\text{sec.}}$$

$$\text{Thrust} = \sqrt{2 \left(\frac{dm}{dt}\right)^2 \frac{Ve}{m}} \quad \text{(momentum change per second)}$$

$$\text{Thrust} = \sqrt{2 (1.36 \times 10^{-6})^2 (8.8 \times 10^{10})}$$

Thrust = 0.57 dynes = 0.58 mg. = 0.00127 millipounds

This value could be off by an order of magnitude or more.

Additional experiments to measure the thrust with an extracting voltage up to 8 KV, a higher beam current, and a heavier collector cone were carried out. A weight was attached to the lower side of the cone to bring its total weight up to 1.064 gm so that the motion of the cone would not be too large and violent with the increased thrust. The results of several trials of the thrust measuring device with various beam voltages are summarized in the following table:

Weight of cone	Max. carbon beam current	Max. accel. voltage	Cone deflection	Weight of carbon collected by cone	Thrust measured with cone	Calculated Thrust	Time used in figuring mass flow rate
0.110gm	6 μa	1950 v.	0.07 cm	0.815 mg	1.2 mg	0.58 mg	600 sec.
1.064	~ 25	9570	0.05		8.5		
1.064	~ 10	7450	0.03		5		
1.064	~ 80	8000	0.08	0.4 mg	13	6 mg	60 sec.

VII. Recommendations for Future Work

There are several recommendations to be made for future work on charged colloidal particle propulsion. In order to achieve the objective of a beam of charged colloidal particles of the order of milliamperes, an ion source which can furnish a much larger positive beam current than our present cold cathode source is necessary. A type which appears suitable with some modification to allow introduction of colloidal carbon is the high current ion source described by Meyerand and Brown[9] which produces 100 ma of ions and can be operated in either the continuous or the pulsed mode. This source uses magnetic focusing, and extraction of positive particles in parallel to the magnetic field lines rather than perpendicular as in our present cold cathode source. In addition, the extraction is through a cathode ring, which accounts for the high ion beam current, which is said to be 1/4 to 1/2 of the electron current in the discharge.

Data on the previous page indicate that we have a factor of a few hundred to go to achieve a thrust of a few millipounds .. An increase in beam current by a factor of 20 and an increase in beam voltage by a factor of 10 would bring us close to the objective.

For future measurements of charge-to-mass ratio of colloidal carbon particles the time-of-flight method is recommended. For path lengths of a meter flight times are the order of a millisecond, about 100 times longer than for ions, so that ions will not interfere with the measurement when the source is pulsed with square pulses 100 μ sec or less in width. The distribution

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9. Meyerand, R. G. and Brown, S. C., "High-Current Ion Source" Rev. Sci. Instr. 30, 110 (1959).

10. Cohen, E. "Research on Charged Colloid Generation," APL TDR 64-75, June 1964.

in time of the collected beam current gives the distribution of charge-to-mass ratio, the smaller values arriving later. A time-of-flight method for charged colloids, which however, is very limited in its ability and design, is described in reference 10.

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