engine replacement in orbit and provides favorable operational characteristics. Relatively advanced stage technology would be employed on the flight configuration of the RNS, but no major feasibility problems have been identified. The capability developed for initial Earth-centered applications would be directly applicable to providing a manned Mars mission capability.

The approach for RNS design has focused on simplicity and large scale module replacement to minimize the equipment and crew required to support the RNS in orbit. A major manned orbital maintenance facility does not appear warranted, and it is also conceivable that an orbital tank farm could be obviated by the space shuttle. The potential of the space shuttle should be exploited to support the RNS. In addition, a space tug could fill a useful role for assembly, maintenance, and engine removal/disposal operations.

Inasmuch as NERVA characteristics were largely selected in an environment of expendable systems, some review would be desirable, particularly to improve its aftercooling characteristics. However, thrust, lifetime, specific impulse, and operating pressure deserve reconsideration specifically for the RNS concept.

The space shuttle has a major impact on the RNS through both space shuttle compatible design configurations for the RNS and propellant resupply operations and economics. Thus, an integrated system definition is essential to achieve a fully effective transportation system.

In conclusion, the RNS, together with the other system elements discussed, has the potential of providing Earth-centered interorbital and lunar transportation at costs that are an order of magnitude below Saturn-Apollo, and even manned Mars landing capability at costs well below current lunar transportation.

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# Alternating Current Operation of a Colloid Source

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**The generation of charged colloids by electrostatic spraying has been adopted to a novel thruster concept in which metal capillary needles are subjected to an a.c. voltage which generates positive and negative current pulses of similar shape and magnitude. This mode of operation may eliminate the need for an electron neutralizer. At thrust levels on the order of $10^{-4}$ lb, the required neutralizer power for the conventional direct current (d.c.) colloid thruster is relatively large compared to the beam power; thus, it would be an advantage to eliminate the requirement for an electron neutralizer for the low-thrust colloid source. Feasibility of this concept has been explored by examining single needle capillary operation. Tests were performed in a bell jar vacuum system and a time-of-flight circuit was built so that thruster parameters could be calculated for the positive and negative pulses. Positive and negative charge-to-mass ratios were obtained in the range of 10,000 coul/kg at a specific impulse on the order of 1000 sec and a beam efficiency of 40%. Results, to date, are encouraging and indicate that a simple, reliable low-thrust system may evolve from this concept.**

## Nomenclature

$g$ = acceleration due to gravity
$L$ = distance from needle tip to collector
$\dot{m}$ = mass flow rate, $dm/dt$
$q/m$ = charge to mass ratio
$T$ = thrust
$t$ = time
T.O.F. = time-of-flight
$V$ = colloid particle velocity
$\epsilon$ = dielectric constant
$i_0$ = needle current
$I_{sp}$ = specific impulse
$V_0$ = accelerating potential

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## Introduction

THE electrohydrodynamic spraying of charged liquid droplets (colloids) from metal capillary needles subjected to high voltages has been extensively investigated with a smaller effort on slit geometry sources and generation of negatively charged colloid beams. The bipolar concept proposed by R. Hunter,[1] expels simultaneously positive and negative charged droplets from metal capillary needles. The bipolar concept presently requires two feed systems, two power supplies, and two propellant types. If the a.c. mode of operation can be perfected, these requirements for elimination of the electron neutralizer will be reduced, and the present study was directed toward this end.

Individual needles have been operated at beam currents above 10 $\mu$amps, $10^4$ coul/kg, and distribution efficiencies of 75%.[2] TRW Systems recently ran an 18-needle d.c. module for 1000 hr at an $I_{sp}$ = 975 sec, 69% efficiency, and 31.3 $\mu$lb

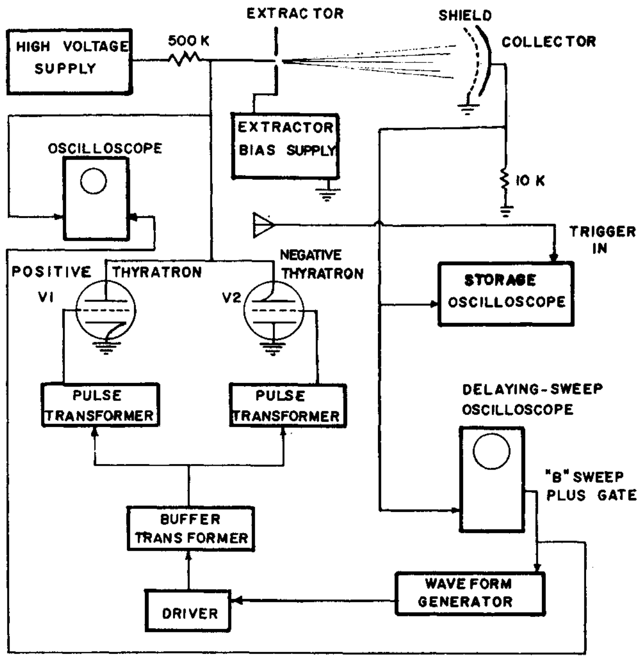



**Fig. 1 Time-of-flight circuit.**

thrust; a neutralizer (electron) was operated during the last 572 hr; a slit was operated at 15 $\mu$lb and 2000 sec for 140 hr. A three-needle colloid source was operated at Air Force Aero Propulsion Lab. (AFAPL[3]) for 3687 hr with very little erosion of the capillary needle tips. TRW and EOS[4] operated bipolar colloid thrusters for 50 hr at a thrust of 50 $\mu$lb with an $I_{sp}$ = 700 sec. These research results for d.c. colloid thrusters have been used as a basis for the design of the a.c. colloid thruster discussed herein.

## Test Set-Up

A block diagram of the circuit used for time-of-flight measurements is shown in Fig. 1. The thyratrons are fired by an adjustable signal, and the voltage on the needle drops below 150 v within 50 nsec after the thyratrons begin to conduct. Since the time-of-flights vary from 5 to 100 $\mu$sec, the maximum error due to this delay is 1%.

The time-of-flight is observed on a storage oscilloscope. The vertical input for this scope is again the beam collector signal. The sweep is triggered by a signal from a small antenna placed near the thyratrons. This trigger signal has been checked on a dual channel oscilloscope and there is no detectable delay between the antenna signal and the beginning of the voltage drop which appears across the series resistor when the thyratrons conduct. To make a time-of-flight measurement, the oscilloscope is operated in the single sweep store mode, the sweep is cocked and the next thyratron

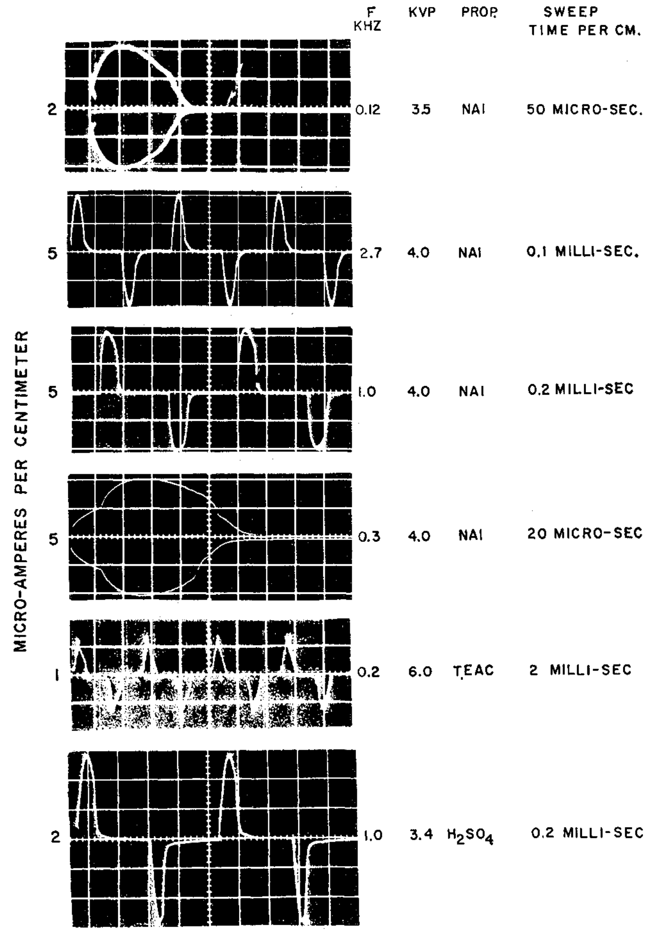



**Fig. 3 Collector current.**

firing causes the sweep to run and display the decay of the beam current.

The relationship of the needle potential to the current at the time of firing is made through the use of still another oscilloscope. The vertical input to this instrument is the high voltage signal from either of the needles. The sweep is triggered by the same "+ gate" used for operation of the thyratron circuit. In order to determine the exact point of the waveform at which the thyratron fired, the trigger point must be advanced 20 $\mu$seconds along the waveform by the delayed-sweep oscilloscope. Photographic records are made of this trace as well as of the T.O.F. on the storage oscilloscope.

The sine wave power supply for this work consists of an audio oscillator which drives a 200-w amplifier which in turn drives a high-voltage transformer with an output of about 4 kv rms each side of center. Present plans call for obtaining specially designed high voltage transformers which will allow

**Fig. 2 Collector current vs collector bias.**

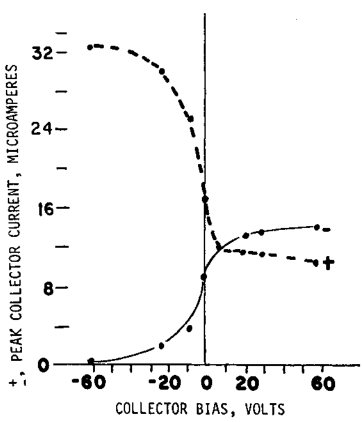
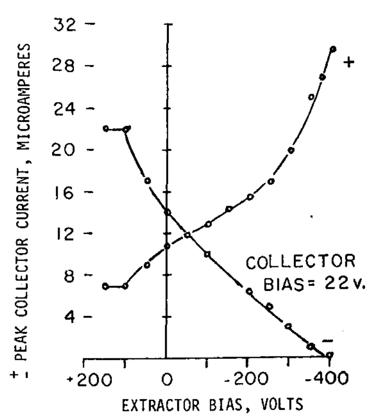



**Fig. 4 Collector current vs extractor bias.**



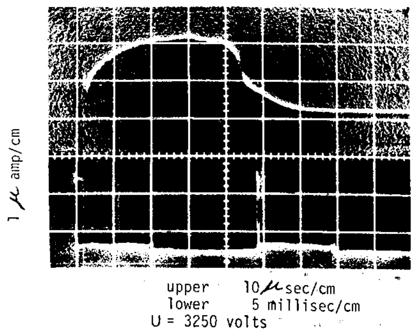



**Fig. 5 Direct-current pulse and spike.**

operation above 10 kHz in order that beam stalling experiments can be conducted as well as experiments with different wave shapes, most particularly square waves. Square wave operation is potentially more efficient due to the more rapid risetime of the voltage and the shorter delay between the times at which the voltage reaches the positive and negative "turn on" threshold of the needle. A 500-v power supply provided the negative extractor bias. A 5.5 in. spherical time-of-flight (T.O.F.) collector was used to obtain T.O.F. current traces on a memory oscilloscope. From these T.O.F. traces the necessary propulsion parameters can be calculated.

The time-of-flight device consists of a shielded collector located at a distance $L$ from the charged droplet source, and its operation is based on the following principles. The electric field configuration at the capillary tip is such that the droplets acquire their terminal velocity within a few millimeters of the tip. The velocity obtained by a particle with charge-to-mass ratio of $(q/m)$ and falling through a potential $U_0$ is

$$V = (2U_0q/m)^{1/2} \tag{1}$$

If the assumption is made that all particles fall through the same potential, there will be a velocity distribution in the beam related to the specific charge distribution of the droplets. The current at the collector is the sum of each of the individual specific charge species. The determination of the $q/m$ distribution in the beam is as follows: $i_0$ is observed on the oscilloscope and then the capillary needle is pulsed to ground potential, triggering the scope and shutting off the capillary potential in approximately a $\mu$sec. The current decay is recorded on the oscilloscope using a memory scope or a camera. The species of droplets having the highest $(q/m)$, and hence the highest velocity, will first stop contributing to the collector current. With the arrival of the last droplet of this species at the collector, the current will drop to a lower level, and likewise down to the slowest species for that of the smallest $q/m$. The time at which the current decays to a new level represents the time required for the last particle of that species to travel from needle to collector and is given by

$$t = L/V = L/(2U_0q/m)^{1/2} \tag{2}$$

$$q/m = L^2/2U_0t^2 \tag{3}$$

Thus, each point on the $i$-$t$ curve relates to a specific value of $(q/m)$ given by Eq. (3).

From the T.O.F. trace, one can obtain

$$\langle t\rangle = \sum_n i\Delta t/i_0 \tag{4}$$

$$\langle t^2\rangle = \sum_n 2n[(\Delta t)^2 i/i_0] \tag{5}$$

The following equations result from the assumption of an equal voltage drop and are the ones which have been used for determining the propulsion parameters from laboratory tests.

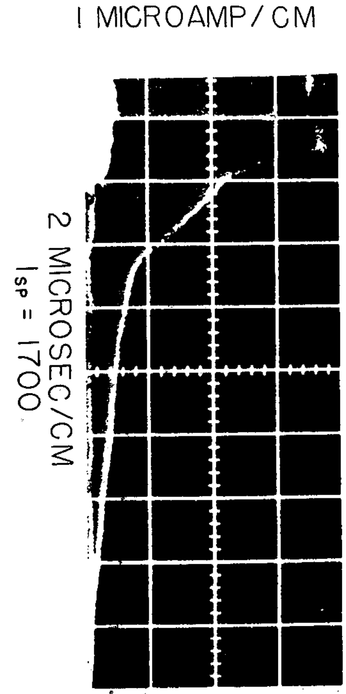



**Fig. 6 T.O.F. direct current spike.**

Charge/mass:

$$\langle q/m^{1/2}\rangle 2 = L^2\eta/2U_0\langle t^2\rangle \tag{6}$$

Distribution efficiency:

$$\eta = \langle t\rangle^2/\langle t^2\rangle \tag{7}$$

Specific impulse:

$$I_{sp} = L\langle t\rangle/g_0\langle t^2\rangle \tag{8}$$

Mass flow rate:

$$\dot{m} = 2U_0i_0\langle t^2\rangle/L^2 \tag{9}$$

Thrust:

$$T = 2U_0i_0\langle t\rangle/L \tag{10}$$

The screen in front of the collector serves two functions. First, it increases the resolution of the device by keeping the collector from "seeing" a charged droplet until the droplet has passed the screen, i.e., traveled the complete distance $L$. Secondly, by making the collector positive relative to the screen, it prevents secondary electrons from leaving the collector and giving an erroneous value to $i$. The effect of secondary electron current on collector current is shown in Fig. 2, where peak collector current vs collector bias is plotted for a.c. operation. A bias of +20 v appears sufficient to prevent secondary electrons from leaving the collector.

## Experimental Results

Several a.c. tests were made using NaI-glycerol, tetraethyl ammonium chloride (TEAC)-glycerol, and $H_2SO_4$-glycerol as the propellant. The frequency ranged from 100–2700 Hz at peak sine wave voltages on the order of 4 kv. Figure 3 shows traces of the current pulses obtained during these tests. It was observed that the current pulses were generally occurring over a small portion of the voltage waveform near the peak and were sensitive to a fairly small change in the extractor bias. Figure 4 shows the effect of varying extractor voltage on the current pulses. The sine wave high-voltage source had an amplitude variation of the order of ±30 v and this caused a noticeable amplitude variation in the current pulses. It is evident the current pulses are quite sensitive to small voltage variations.

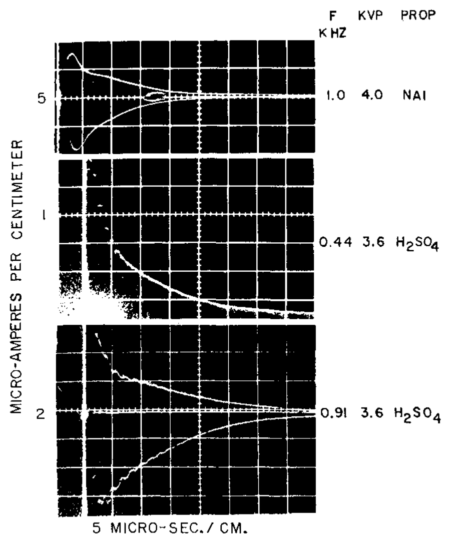



**Fig. 7 T.O.F. traces.**

It is interesting that the current pulses obtained during a.c. operation were quite similar to the current spike at the start of a square current pulse obtained at a low d.c. voltage (Fig. 5). The upper trace is the current spike on an expanded time scale compared to the lower trace. A T.O.F. trace taken at the top of the spike is shown in Fig. 6. It is quite similar to those obtained during a.c. operation. Another interesting item is that NaI-glycerol sprays well at positive d.c. voltages but is very "hashy" at negative d.c. voltages; however, during a.c. operation it sprayed satisfactorily at both polarities. This probably is associated with the fact that unstable d.c. operation is due to free hydrogen production and bubble nucleation, while during a.c. operation the hydrogen combines with free iodine liberated during the positive half cycle, ultimately resulting in lower vapor pressure end products.

The propellants used in these tests produced positive and negative current pulses of approximately equal magnitude and shape with the proper extractor bias. At zero extractor bias the negative pulse generally had a greater peak magnitude than the positive pulse. An application of $-25$ to $-75$ v on the extractor would be sufficient to equalize the height of the two pulses. During some periods of operation, the positive pulse would be wider than the negative; this would require a greater height for the negative pulse so as to provide equal plus and minus charge emission.

The $H_2SO_4$ glycerol and NaI-glycerol propellants gave similar operating results except that the $H_2SO_4$ mixture gave more efficient T.O.F. traces on the negative pulse and would operate without any visible glow at the needle tip. The NaI operation always had a slightly visible glow. The TEAC-glycerol mixture provided very similar plus and minus pulses but the charge-to-mass ratio was too low to be of interest. This was found to be true for TEAC-glycerol mixtures operating with a d.c. voltage source.

To determine approximate thruster parameters during a current pulse the following approach was used. T.O.F.

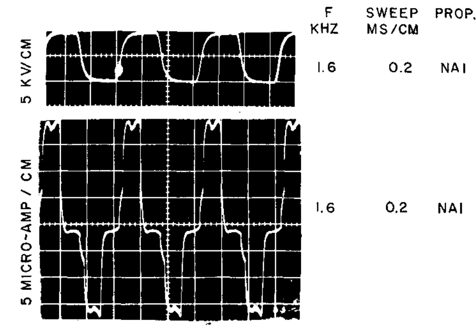



**Fig. 8 Square wave traces.**

traces were taken at several points on the current waveform as seen on the oscilloscope. The thrust, $I_{sp}$, $\dot{m}$, $q/m$, and efficiency were calculated at each of these points. Each parameter ($p$) calculated was multiplied by the peak current for that T.O.F. trace and plotted vs time for each pulse. A curve could then be drawn through these points to represent $ip$ vs time where $p$ is the parameter of interest. An average $p$ can be calculated by

$$\bar{p} = \int_0^t ipdt \Big/ \int_0^t idt$$

where

$$\int_0^t idt$$

is the total charge of the current pulse as seen on the oscilloscope. The thrust ($T_{ave}$) was determined by multiplying the total impulse per pulse by the frequency. Table 1 shows the results of these calculations. Figure 7 shows some representative T.O.F. traces obtained during the tests.

Peak currents have been obtained up to 40 $\mu$amp during a.c. operation, which is about five times the peak current for which the parameters in Table 1 were calculated. Running at these current levels and doubling the frequency should bring the thrust per needle for a.c. operation up to the level obtained by d.c. spraying.

The use of a square wave voltage source may be better than using a sine wave if the following is true; the mechanical relaxation time of the spraying jets is long compared to the switching time of the square wave pulse and the resistance of the spraying jet is low enough to allow charge reversal in the jet as the square wave reverses polarity. An attempt was made to run with a square wave. A flight-type square wave source developed for an ion engine flight test has used. The power supply failed after a short time, but thruster operation was achieved as shown in Fig. 8.

## Space Charge Considerations

The colloid needle has not been observed to run in a space-charge limited mode; however, the space charge of an individual current pulse can cause the charged droplets to accelerate radially resulting in beam spread. For an initially cylindrical beam, the equation for the beam spread angle

**Table 1 Propulsion parameters for a.c. operation**

| Propellant | $\rho$, ohm/cm | $f$, cycles/sec | $T_{ave}$, $\mu$lb | | $\bar{T}_{\pm}$ $\mu$lb/pulse | $\bar{\bar{I}}_{sp}$, sec | $\bar{\eta}$, % | $\bar{\dot{m}}$, kg/sec | $\overline{\langle q/m^{1/2}\rangle^2}$, coul/kg |
|---|---|---|---|---|---|---|---|---|---|
| $H_2SO_4$ Glycerol | $7 \times 10^2$ 30°C | 230 | 0.16 | + | 1.42 | 860 | 36 | $1.9 \times 10^{-10}$ | $1.25 \times 10^4$ |
| | | | | − | 2.26 | 854 | 50 | $2.95 \times 10^{-10}$ | $1.15 \times 10^4$ |
| $H_2SO_4$ Glycerol | $7 \times 10^2$ 30°C | 910 | 0.45 | + | 1.75 | 890 | 38 | $2.54 \times 10^{-10}$ | $1.16 \times 10^3$ |
| | | | | − | 2.60 | 815 | 53 | $3.85 \times 10^{-10}$ | $9.65 \times 10^4$ |
| NaI Glycerol | $2.9 \times 10^3$ 30°C | 440 | 0.14 | + | 1.70 | 1050 | 42 | $1.8 \times 10^{-10}$ | $1.23 \times 10^4$ |
| | | | | − | 1.30 | 985 | 42 | $1 \times 10^{-10}$ | $1.53 \times 10^4$ |

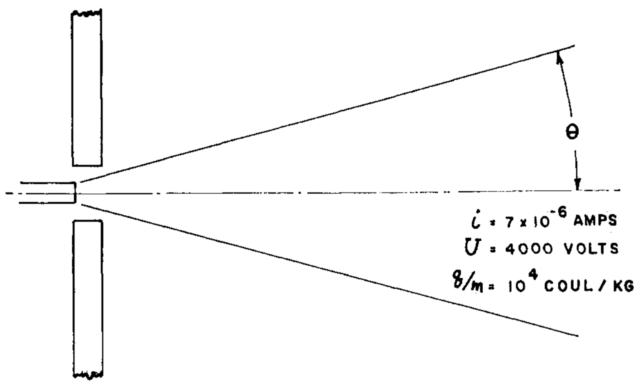



**Fig. 9 Beam spread.**

which is valid for a non space-charge limited beam[5]:

$$\tan\theta = r/L \approx (i(2m/q)^{1/2}/U^{3/2}\epsilon\pi)^{1/2} \quad (11)$$

Substituting the values listed in Fig. 9 which are based on test data, we find $\theta = 6.7°$. Hence the beam spread due to space charge is small compared to the beam spread caused by the emitting jets not being parallel to the desired thrust axis. This beam spread, due to the space charge, could be decreased by holding the voltage constant and operating at higher frequencies which would decrease the average current per pulse.

The potential due to a point charge in the presence of a charged, insulated conducting sphere (see Fig. 10) is given by[6]

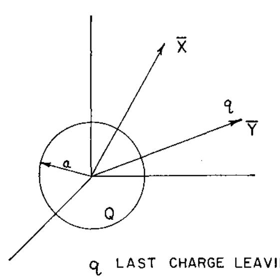
$$U = (q/4\pi\epsilon|\bar{x} - \bar{y}|) - aq/4\pi\epsilon|\bar{x} - (a/y)^2\bar{y}|y + (Q + aq/y)/4\pi\epsilon\bar{x} \quad (12)$$

If $\bar{x}$ is along $\bar{y}$ and $a \simeq y$ than $U = Q + q/4\pi\epsilon\bar{x}$ where $q$ is the charge of the last particle leaving the needle and $\epsilon$ is the dielectric constant of free space.

For a final spacecraft charge of $5 \times 10^{-10}$ coulombs and a radius of 0.5 m, $U = 9$ v is the retarding potential seen by last charged droplet leaving the source.

From these discussions, it appears that space charge and spacecraft potential effects may be negligible for single needle currents. However, for large currents, the problem can be solved by operating adjoining needles with their applied voltages 180° out of phase. This mode of operation can also provide control over the current output on the positive and negative pulses so as to obtain equal plus and minus currents. A test was run in the laboratory with two needles 180° out of phase.

Two capillary needle sources with separate fuel supplies were mounted in the vacuum chamber. The high voltage transformer was center tapped and a needle was attached to each end of the transformer (see Fig. 11). $H_2SO_4$-Glycerol or NaI-Glycerol was used as a common propellant. Figure 12 shows the current to the collector and T.O.F. traces taken on the current pulses. It was hoped that the positive and negative current pulses would be emitted simultaneously from the two needles and cancel at the collector. However, it is seen that the two pulses overlapped, but the positive and negative portions were approximately equal. It was determined, after the test, that the overlapping is due to a phase shift of approximately $0.5\pi$ rad in the voltages caused by the attachment of the T.O.F. circuit to one of the needles. The operation of a large number of needles with the proper control in the above mode should result in a net neutral beam per pulse.




q LAST CHARGE LEAVING SPACECRAFT
Q FINAL CHARGE ON SPACECRAFT

**Fig. 10 Conducting sphere.**

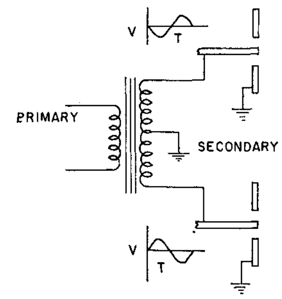



**Fig. 11 Two-needle a.c. operation.**

## Power Conditioning Considerations

As part of this effort it seemed appropriate to consider the requirements to be imposed on power conditioning and propellant supply systems for the operation of an a.c. thruster in space and to produce a conceptual design of such a system. Accordingly, Fig. 13 shows a block diagram of such a system.

### Propellant Supply

In general, the needles respond relatively slowly to changes in propellant supply conditions, so it was decided to not to attempt to use the propellant supply system as a means of exercising precise control of the thruster but only to use it to turn propellant on and off and to maintain constant propellant pressure.

Since the propellant may have resistivity about 2600 ohm/cm or lower, two propellant supply tanks are required to prevent unnecessary electrical loads. These supply tanks will be of some type of zero gravity configurations; for example, a collapsing bladder or a design which takes advantage of capillary forces. The complete feed system will be so designed as to require an externally applied positive pressure in order that the needles will spray continuously. This pressure will be supplied from a central reservoir and will be determined and maintained independently for each supply tank by the feed system controller. There will also be two electrically operated propellant shut-off valves. These valves will be of the smallest possible volume and will be located as close to the needles as possible in order that the needles respond quickly to valve actuation.

### Power Supply

The whole concept of the a.c. thruster has been intended to lead to simplified, lighterweight power conditioning systems. The d.c. bipolar or electrodeless thruster requires two power supplies. The proposed design will be an a.c. bipolar array with the two sets of needles connected to opposite ends of a center-tapped high voltage secondary winding.

The power supply frequency will be determined by a unijunction oscillator or clock. The unijunction circuit was chosen because of its inherently good stability. The output of the clock is used to trigger a flip-flop whose output is in turn fed to a driver consisting of two medium power transistors operated in push-pull.

The return of the driver transformer is through a control transistor which is used to turn the driver on and off in response to either an on-off command from the programmer or in response to an over current indication from $A_3$, the differential current signal amplifier. An over current condition on either half of the power supply will cause shutdown as follows: the output from $A_3$ is fed to a "Schmidt" type circuit which will

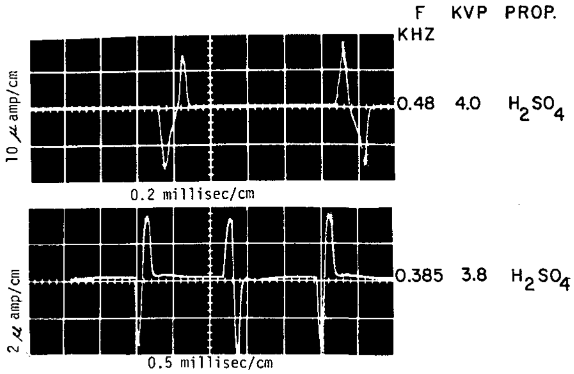



**Fig. 12 Collector current, two-needle operation.**

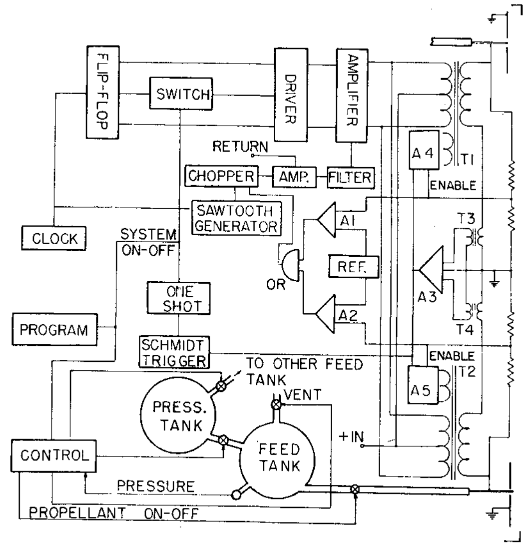



**Fig. 13 Power conditioning.**

trip on either polarity and which averages over several cycles; the output from the "Schmidt" circuit drives a "one-shot" which shuts the power supply down for, say, 20 msec and then attempts to turn it back on. This sequence will repeat until either the overload clears or the system is programed off.

At any other than overload conditions the current balance between the needles is maintained by the two amplifiers $A_4$ and $A_5$ which will respond to the differential output of $A_3$ by either increasing or decreasing the d.c. saturation level in $T_1$ or $T_2$, respectively.

The input to $A_3$ is from the two current transformers $T_3$ and $T_4$. Since our experience has been that in the event of current unbalance, the positive needle has the greatest current, the decision was to reduce positive current rather than try to increase negative. Thus, $A_4$ and $A_5$ are enabled only when their respective transformers have a positive output.

The two transformers $T_1$ and $T_2$ are connected in parallel to the output amplifier. The output amplifier receives its switching signal from the driver and its power from the regulated power supply which is composed of the filter, amplifier, chopper, sawtooth generator, error, and reference circuitry. This regulated supply is a type of switching regulator. The sawtooth generator is slaved to the clock and supplies a linear ramp to the "chopper" which is again a Schmidt type circuit. This sawtooth rides on a d.c. bias determined by the reference and the amplifiers $A_1$, $A_2$, and $A_3$. This bias determines the width of the pulse from the chopper and, thus, the output level from the supply. The output of $A_3$ is used to alter the output of the reference circuit in such a manner that a called-for increase or decrease in one of the needle voltages will not be opposed by the regulator. It almost goes without saying that there are certain to be a number of problems to be solved in actually building this supply; however, this is a concept which shows how simply the a.c. thruster might be operated in space.

## Summary

The results of tests on a.c. colloid operation have demonstrated the feasability of the concept. Beam spread due to space charge can be reduced by holding the voltage constant and increasing the frequency. Spacecraft potential, beam spread, and current control problems can be eliminated by operation of two sets of needles with the applied voltages 180° out of phase. Operation of two sets of needles requires two separate feed systems or development of a high-voltage isolator, either of which is an additional complication. At the frequencies used in these tests there does not appear to be a fluid mechanical limitation on the spraying mechanism; spraying occurred at all frequencies used.

At present, the efficiency is lower during a.c. operation compared to the d.c. mode. Further research may result in higher efficiencies; however, at the efficiencies now obtainable, it appears that the a.c. mode is applicable to thrust levels up to 100 μlb due to the elimination of the electron neutralizer. Also, if the lifetime of the electron neutralizer appears to be substantially less than the capillary needles, one may at the higher thrust levels, sacrifice efficiency for lifetime and use an a.c. colloid source. The a.c. thruster may be a less complicated system if the control of total charge per emitted current pulse is not too difficult, a possible method for regulating the total charge emitted from the source appears feasible but has not been tested. This is another area which requires more investigation.

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