TR-66-94

RESEARCH ON CHARGED PARTICLE ELECTROSTATIC THRUSTORS

E. COHEN and M. N. HUBERMAN

TRW Systems

TECHNICAL REPORT AFAPL-TR-66-94

SEPTEMBER 1966

AIR FORCE AERO PROPULSION LABORATORY
RESEARCH AND TECHNOLOGY DIVISION
AIR FORCE SYSTEMS COMMAND
Wright-Patterson Air Force Base, Ohio

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4490-6013-R000

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FOREWORD

This document was prepared by TRW Systems, Redondo Beach, California. under USAF Contract No. AF33(615)-2817. The work was administered by Air Force Aero Propulsion Laboratory, APIE, Research and Technology Division, Wright-Patterson Air Force Base, Ohio. Mr. William C. Burson served as Technical Monitor.

This interim report covers the first year of a two-year program. The work described extends from the period July 15, 1965 to August 15, 1966. The work was performed in the Electric Propulsion Technology Department which is a part of the Propulsion Technology Laboratory. Mr. Ernest Cohen was Project Manager of the Contract.

Acknowledgements are recorded for the substantial contributions made by several members of the Electric Propulsion Technology Department. These include J. Caldwell, S. G. Forbes, R. Gohl, R. Kemp, P. Kidd, H. Shelton, and C. J. Somol. W. Daley, J. Felig, N. Law and A. Seaton were invaluable aids in their capacity as technical support.

The fruitful discussions with Professor C. D. Hendricks, University of Illinois, are gratefully acknowledged.

The early guidance and encouragement of this program by Robert E. Hunter and S. Wineland must be emphasized. A great debt is owed to William Burson whose patience and understanding made the transition of Technical Monitor an efficient and smooth procedure.

This interim report was submitted by the authors, September 1966.

Publication of this report does not constitute Air Force approval of the report findings or conclusions. It is published only for the exchange and stimulation of ideas.

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ABSTRACT

This research program is intended to extend the state-of-the-art in heavy particle electrostatic propulsion. The following target goals were set:

a.	Thrust	2.0 (millipounds)
b.	Specific Impulse	1500 (seconds)
c.	Efficiency	75 percent
d.	Life	75 hours

With these goals in mind, the work performed in the first half of the program is described particularly as it relates to the average charge/mass ratios obtained, charged particle beam currents, beam neutralization and post acceleration with 100 KV.

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SYMBOLS

KV	kilovolt
T.O.F.	time-of-flight
Q/M	charge/mass
I_{sp}	specific impulse
in. or "	inch
O.D.	outside diameter
I.D.	inside diameter
Pt	platinum
NaI	sodium iodide
H_2SO_4	sulphuric acid
cm.	centimeter
$\overline{(Q/M)}$	average charge/mass ratio
V_N	capillary tube voltage
P	pressure
I_T	total needle or beam current
V_{xtr}	extractor electrode potential
V_{spr}	suppressor potential
V_{cone}	cone potential
V_{screen}	screen potential
Kg/sec	kilograms per second
"g"	acceleration due to gravity
Hg	mercury
LN_2	liquid nitrogen
°C	degrees centigrade
η	efficiency
T_c	thrust incident upon collector
ΣT	total thrust exerted by charged beam
μa	microamperes
μlb	micropounds thrust
H_2	hydrogen
CO	carbon monoxide

CO_2	carbon dioxide
amu	atomic mass units
MR/Hr	milliroentgens per hour
Å	Angstrom
I_N	needle or beam current
I_c	collector current
I_{Neu}	neutralizer current
I_{xtr}	extractor current
I_s	shield current
V_c	floating collector voltage
T	thrustor
$\dot{m}$	mass flow rate
i	current
v	velocity
V	potential or voltage
T_1, T_2	period of oscillation
I_1, I_2	moment of inertia
K	torsion constant

I. INTRODUCTION

This interim report describes and summarizes the work performed on Contract AF33(615)-2817 between the period 15 July 1965 - 15 August 1966. This research is directed toward the eventual demonstration of efficient electrostatic engine operation at specific impulses of 1000 seconds and above. This program is intended to extend the state-of-the-art in heavy particle electrostatic propulsion by achieving the following target goals.

Thrust	2.0 millipounds
Specific Impulse	1500 seconds
Efficiency	75%
Life	75 hours

The heavy particle or colloid thrustor produces thrust basically in the same fashion as an ion engine, i.e. by the reaction between a charged beam and an electric field. The neutralization of either beam is accomplished by similar techniques, the injection of electrons. The similarity stops here. The charged beam in the ion engine consists of ions of a single fixed specific charge and a small number of neutrals. The colloid beam contains charged multimolecular or heavy particles having a relatively narrow velocity dispersion. This spread in specific charge is peaked about an average value which may be shifted over three decades, from less than 200 coulombs/kilogram to over 300,000 coulombs/kilogram. For comparison purposes the specific charge of cesium is 720,000 coulombs/kilogram. It is just this ability to vary the position of the peak of the specific charge distribution and therefore the specific impulse of the heavy particle thrustor which allows mission parameters to be optimized.

The TRW Systems colloid thrustor produces a beam of charged droplets by exposing an electrically conducting liquid to the intense field produced at the tip of a capillary tube held at a positive potential, nominally six thousand volts.[1,2,3] Each capillary tube is centered within an extractor aperture. The extractor is held negative at a nominal 500 volts in order to produce an electron barrier to the capillary tubes. Figure 1 is a photograph of a 60 needle module which has been operated at 1 milliampere beam current. Also shown in this figure is a honeycomb collector, part of a torsion pendulum assembly used for measuring thrust.

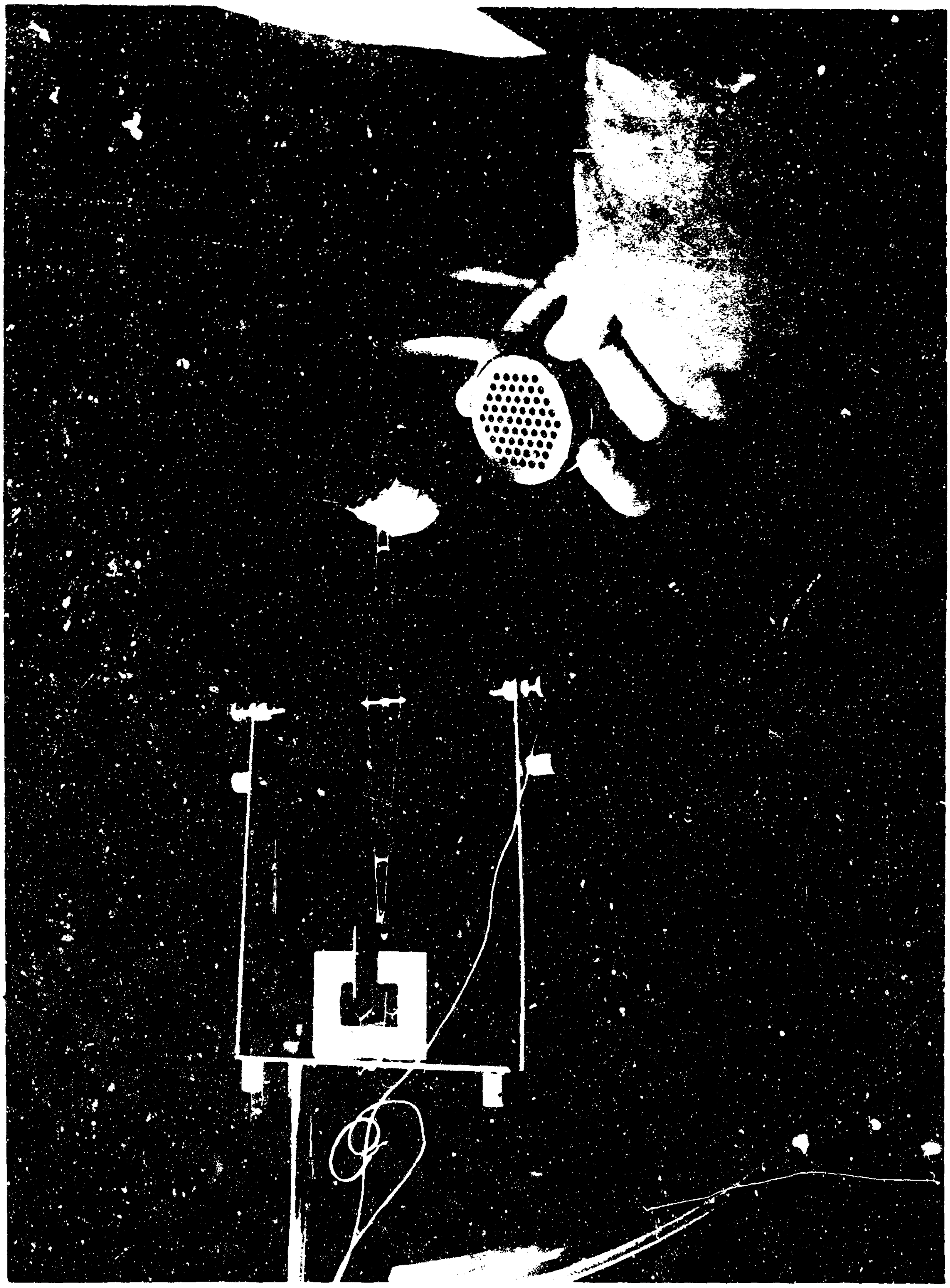


Figure 1. 60 Needle Module and Thrust Balance.

The range of specific charge is obtained by the variation of four parameters; these are the mass flow rate, the fluid resistivity, the selection of ionizer additive and the potential difference between capillary tube and extractor electrode. The theoretical understanding of the effects of these parameters is not yet on firm enough ground to allow a prediction of the average specific charge and beam current yield to be made. On the other hand considerable laboratory data has been obtained and this information permits certain generalizations to be made. The laboratory data has been obtained from single capillary tubes, 6 tubes, 16 tubes, 36 tubes or 60 capillary tubes mounted in a single module. Based upon the beam current requirements for maximum thrust, the required number of needles are then paralleled within a single module. Throttling of the beam is accomplished by either decreasing the needle potential or decreasing the mass flow rate.

Within the normal thrustor operating range, the ratio of thrust to beam current is equal to approximately 1.8 micronewtons (0.4 micropounds) per microampere. This is illustrated in Figure 2 in which total thrust is plotted (with efficiency corrections) vs current. Since the data for this figure were obtained by varying the propellent feed rate and extraction voltage, Figure 2 also demonstrates that a given configuration can be throttled over a 15-to-1 range.

Figure 3 shows the variation of thrust with specific impulse and demonstrates that by adjusting feed and voltage parameters to obtain approximately constant current, it is possible to vary the specific impulse at constant thrust in order to meet specific mission requirements.

The forces exerted on the liquid surface are surface tension, the liquid feed pressure and the electric pressure produced by the field. The combination of these three forces produces an unstable liquid surface from which charged multimolecular droplets are continuously ejected at high velocity to produce a resultant thrust. Capillary tubes are operated in parallel to obtain the desired maximum thrust.

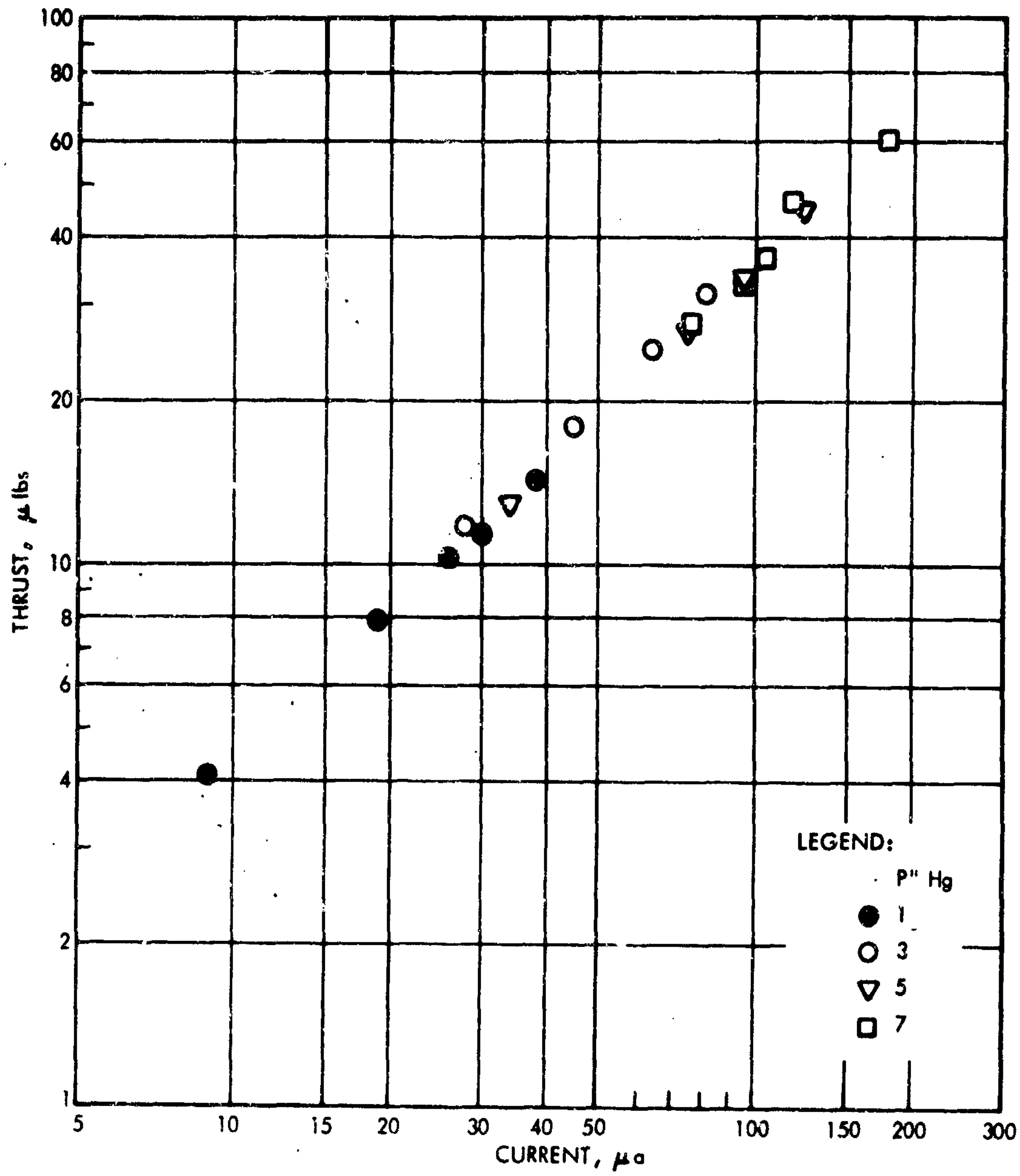


Figure 2. Thrust vs Current.

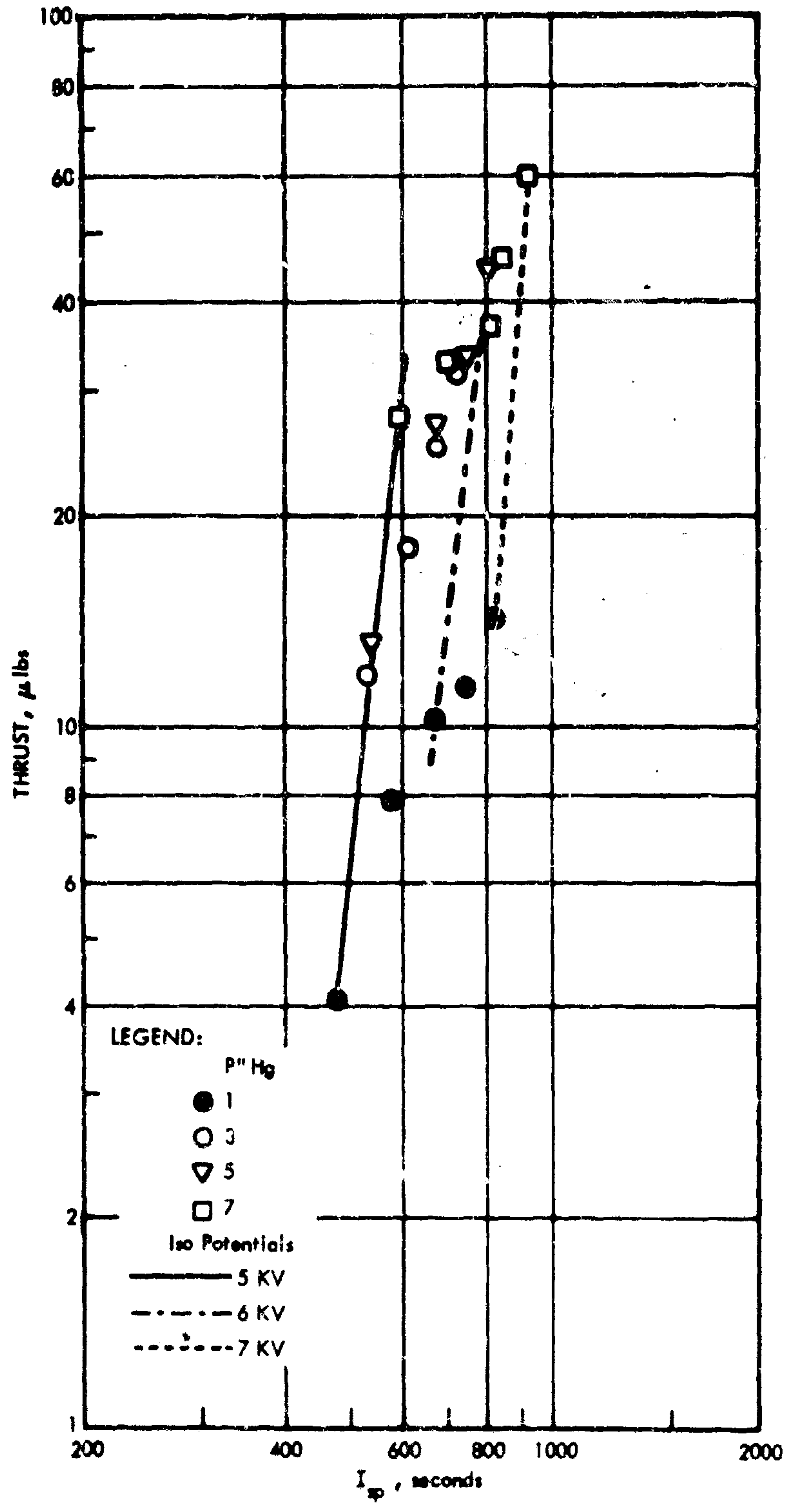


Figure 3. Thrust vs I_{sp}.

The efficiency of charged particle generation, as distinct from overall thrustor efficiency, is high for the colloid thrustor. However when considering the overall, or rocket thrust efficiency, two sources of performance degradation must be taken into account.

One of these, common to all thrustors, is the divergence of the exit beam. A typical value of beam divergence efficiency is 90 percent. The second efficiency factor to be considered is directly related to the spread in specific charge of the particles in the exhaust beam. This factor is somewhat independent of the specific impulse; it is more specifically a function of the shape of the capillary tips and the uniformity of the capillary bore. The state-of-the-art performance gives specific charge distribution efficiencies ranging from 65 to 80 percent. This may be compared to individual capillary specific charge distribution efficiencies as high as 90 percent and better.

In practice, although representative specific charge peaks have been obtained over many decades, the normal range in laboratory practice extends from 200 to 10,000 coulombs/kilogram. At the nominal six kilovolts capillary potential, a resultant specific impulse of 140 seconds to 1000 seconds results. It should be kept in mind that post acceleration techniques may be used to increase the specific impulse to higher values. Voltages of 100 Kv have been utilized at TRW Systems in order to obtain values of specific impulse of 2000 seconds.

II. SUMMARY

In order to design an electrostatic engine utilizing post acceleration techniques considerable knowledge is required regarding the behavior of a single capillary needle, an ensemble of paralleled needles, the neutralization of the positive beam, the technology associated with maintaining a high voltage utilizing a liquid propellant environment, and finally a convenient method of analyzing the results of an experiment. A considerable fraction of this knowledge has been acquired during this report period. The results are tabulated in the following list.

A. Single Needle

1) A platinum needle was operated for 120 hours with no apparent corrosion at the tip as observed at 100X magnification. The current averaged 24 microamperes with an average charge/mass ratio of 6500 coulombs/kilogram calculated from the average mass flow rate.

2) Another platinum needle was run for 164 hours; time-of-flight (T.O.F.) data indicated a needle current of 13 microamperes, an efficiency of 77 percent and an average charge/mass (Q/M) ratio of 2600 coulombs/kilogram.

B. Module (Ensemble of 6 Capillary Needles)

1) A module containing six needles using glycerol-H_2SO_4 as a propellant was operated continuously for 94 hours at a beam current of 80 microamperes. The Q/M was varied between 4000 and 9000 coulombs/kilogram at an efficiency of 75%.

2) A six needle module using NaI as an additive was operated continuously for 172 hours at 80 microamperes. No corrosion of the needle tips was observed. Although the system parameters were unchanged the average Q/M ratio varied from 3000 to 5000 coulombs/kilogram. However, the square of the mean root Q/M ratio held relatively constant at 4000 coulombs/kilogram. The efficiency for this run was generally just better than 75 percent. The values of thrust obtained from T.O.F. data averaged 25 micropounds. The thrust is corrected for velocity dispersion but not for beam divergence.

C. Module (Ensemble of 37 Needles)

A 37 needle module, propellant fluid glycerol-NaI, was operated for 235 hours in a continuous run. For 67 of these hours, the module was full on averaging 300 microamperes. During the remaining time, evenings and weekends, the microthrustor was throttled. The square of the mean root Q/M ratio averaged 4000 coulombs/kilogram. The I_{sp} corrected for efficiency was 680 seconds. No needle tip erosion was apparent. Beam currents were d.c. with no appreciable arcing observed.

D. Module (Ensemble of 60 Needles)

1) A 60 needle module was operated at 700 microamperes during a hot wire neutralization experiment.

2) The same module was run with a beam current of one milliampere during a plasma neut alizer experiment.

3) This high density module appears to work more satisfactorily at 500 microamperes. At present it is not known whether this effect is due to the residual pressure in the vacuum chamber. A single needle can be operated successfully with no serious arcing at 15 microamperes. The 60 needle module should emit 900 microamperes with little arcing. It does not do this in a 4 by 8 foot vacuum tank.

E. Several Comments on Needle Efficiency - State of the Art

Although there is not yet available a firm theoretical understanding of the relationships between the various parameters which effect charged droplet emission by a conducting liquid from the end of a capillary tube whose tip is exposed to a strong electric field, much experimental evidence has been acquired to justify the following statements. In the low charge/mass regime, up to 1000 coulombs/kilogram, Q/M distribution efficiencies run 90 percent for a single needle and short time runs, about 100 hours. The 100 hour life figure is presented because no attempt has been made to allow such a needle to operate much longer. At this stage such a task is considered trivial.

From 1000 coulombs/kilogram to perhaps 10,000 coulombs/kilogram the efficiency for a single needle very often ranges from 80 to 85 percent for a time normally extending from 25 to > 100 hours. No emphasis has been placed on Q/M ratios greater than 10,000 coulombs/kilogram and therefore less laboratory work is available to justify a strong statement. However, some evidence is on hand to indicate that efficiencies between 50 and 75 percent can be obtained.

In the 1000 to 10,000 Q/M range, the lifetime for an 85 percent efficiency single needle demands some additional explanation. Many individual needles have been operated in excess of 100 hours with no visible tip corrosion. There have been a smaller number of cases where tip erosion has been observed. In cases of tip erosion a discharge is normally the cause of the failure. This will occur in a poor vacuum station or can be artifically produced by removing the electron trap. Lowering the negative saddlepoint potential just downstream of the capillary tube will accomplish this.

Nevertheless even when no tip corr- .on exists a gradual decrease of needle efficiency may show up with time. : evidence at present appears to indicate either a deposit of material at the eedle rim or a condensation of organics in the vacuum system upon both extractor and needle. The condensation of organics can be prevented by appropriate temperatures on the needle-extractor assembly and cold trapping elsewhere. Such an attack was successfully used in the past year in a successful 100 hour run[3].

With an ensemble of capillary tubes, it will be observed that in general efficiency figures are found between 65 and 78 percent and in common with a single needle a decrease in efficiency occurs with time. This latter effect is undoubtedly due to the same factor described for the example of an individual needle. The former effect, a lower efficiency for an ensemble as contrasted to a single needle, is probably due to the noticeable variance in needle rim geometry among a group of capillary tubes. At the present time, needle tips are hand generated and not selected for uniformity. Work is proceeding on a program to insure needle uniformity. It is anticipated that such uniformity will result in ensemble efficiencies consistently closer to single needle performance.

F. Heavy Particle Neutralization

Using a floating collector technique, neutralization of a positive heavy particle beam has been demonstrated by both an immersed hot wire tungsten emitter and with a cesium plasma neutralizer positioned just outside of the beam.

G. Post Acceleration, High Voltage

A modest beam of 125 microamperes has been accelerated with 100,000 volts and operated for eight hours before termination.

H. Diagnostics - Time-of-Flight Data Processing

A computer program has been generated which nearly eliminates the arduous reduction of data formerly necessary in the interpretation of T.O.F. traces. In addition results are obtained faster and with greater accuracy.

III. SINGLE NEEDLE RESEARCH

Research on individual needles is a continuing part of the overall program. The emphasis during the past year has been confined almost entirely to the behavior of a standard needle and a standard fluid. The needle is a thin rim platinum capillary tube with an 0.014 in. outside diameter and an 0.004 in. inside diameter. The propellant in use is a mixture of glycerol droped with NaI to give a resistivity of $\sim$ 4700 ohm cm at 25°C. At the present the NaI additive is used because it produces a steady current. Although H_2SO_4 has been used in the past, it produces currents somewhat less steady than with NaI. The glycerol-H_2SO_4 mixture however was used for the post acceleration 100 KV run to be described further on. It is planned to try other additives in the future. Initially an 0.014 by 0.008 in. capillary was used. This was stuffed with an 0.005 in. diameter platinum wire. Although the technique was satisfactory, the smaller diameter platinum capillary was adapted as a standard because of its simplicity. Representative runs are identified by a code number which lists the year, monthly report and run number. A schematic of the testing fixture is shown in Figure 4

A. Needle Performance

1) Run 6511-01

The data was obtained with an 0.014 in. I.D. by 0.008 in. I.D. platinum capillary stuffed with 0.005 in. diameter platinum wire. The propellant, glycerol and NaI had a resistivity $\sim$ 4600 ohm cm. The efficiency was equal to or greater than 75 percent for all of the data. The efficiency does not take into consideration the divergence of the beam but is defined as the ratio of the square of the mean root charge/mass ratio by the average charge/mass ratio.[4] The divergence factor which is discussed in Section IV is $\sim$ 90 percent. Figure 5 is a graph of the data and is representative of much of the earlier single needle tests. Needle currents, a function of feed pressure and needle potential, were in general less than ten microamperes. The electronics involved with T.O.F. interpretation at this time make Q/M ratio determination uncertain above 2500 coulombs/kilogram.

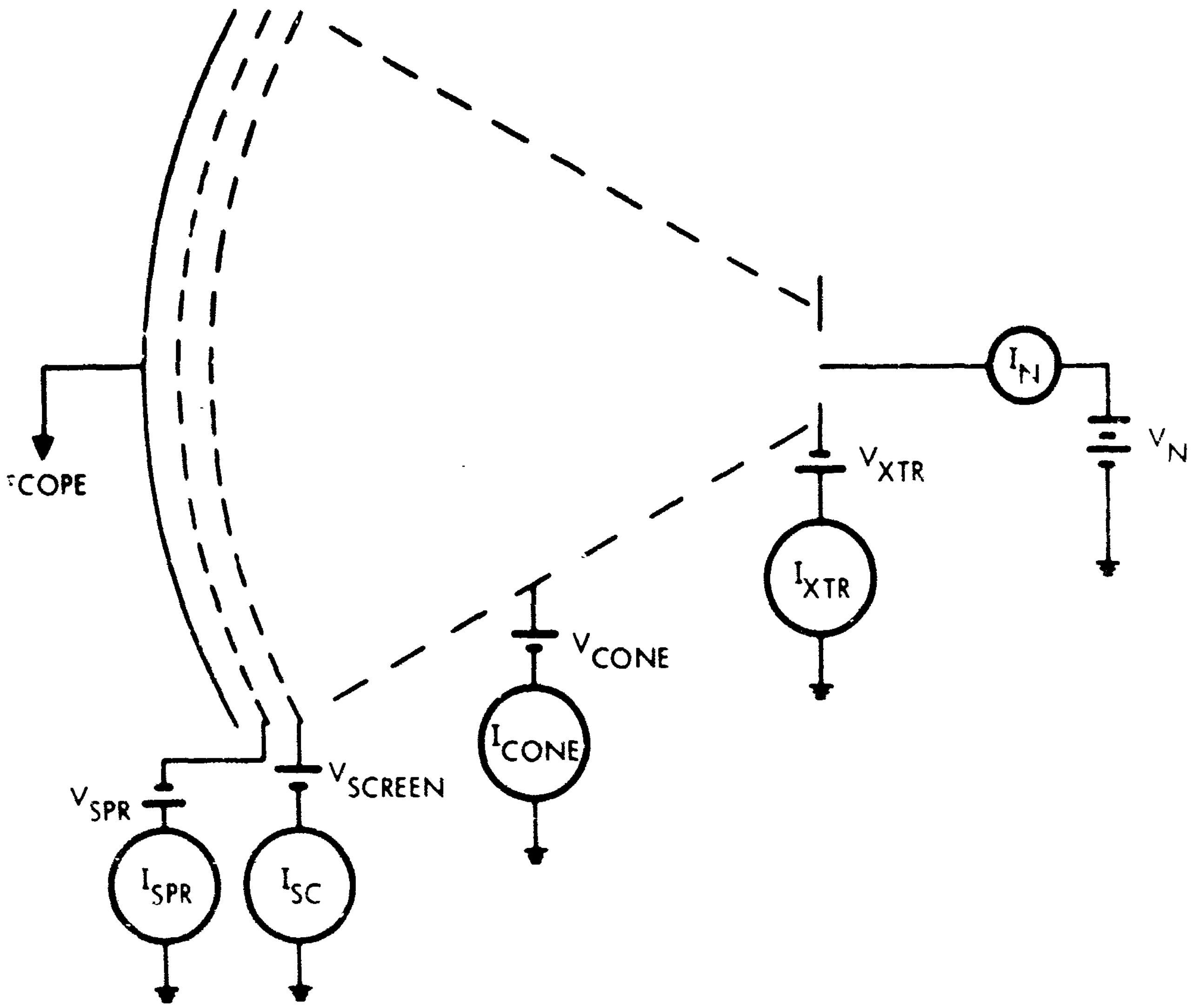


Figure 4. Needle Testing Schematic.

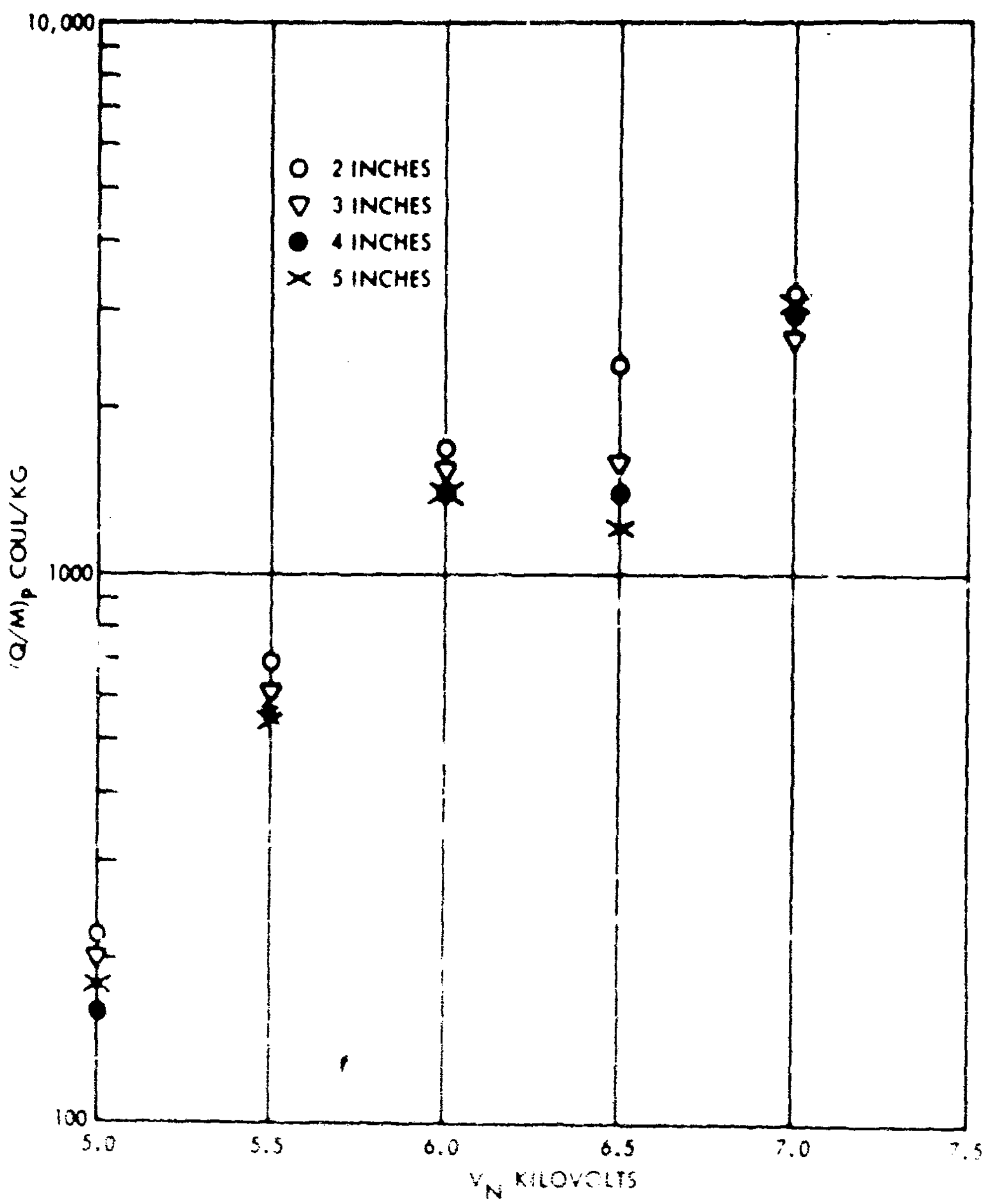


Figure 5. Q/M vs V_N 6511-01.

2) Run 6512-01, 02

As in the previous run, an 0.014 by 0.008 stuffed Pt needle was used to obtain an average for peak charge/mass ratio and current as a function of needle potential and feed pressure. The propellant was glycerol doped with NaI, resistivity ≈ 4600 ohm cm. Although a longer T.O.F. distance was used, 20 cm instead of the previous 10 cm, "dead times" again made Q/M values above 2500 coulombs/kilogram uncertain. A continuous run of 36 hours was made in order to obtain the data shown in the two tables. Table 1 was obtained during the first day of the run, Table 2 a day later. The mass flow rate efficiencies discussed previously were greater than 72 percent.

3) Standard Needles

The data described earlier was taken with an 0.014 by 0.008 inch platinum needle stuffed with 5 mil platinum wire. The function of the stuffed wire was to increase the flow rate impedance of the capillary tube. Because the wire stuffing operation took time and in an attempt to make capillary flow more uniform, advantage was taken to the in-house work of Hunter and Wineland of AFAPL at Wright Patterson. This led to the use of a 0.014 in. O.D. by 0.004 in. I.D. capillary. Peaked Q/M ratios in access of 3000 coulombs/kilogram and adequate (> 75 percent) efficiencies were easily obtained. Currents of 10 microamperes per needle were common.

Table 1 6512-01

V_N kv	P in. hg	I_T μ_a	$\overline{(Q/M)}$ coulombs/kg
5.0	0.4	0.71	935
5.5	↓	1.6	2750
6.0	↓	1.63	2720
6.5	↓	2.1	3350
7.0	↓	2.3	4500
7.5	↓	1.[illegible]	3400
8.0	↓	3.0	4700
8.5	↓	3.0	4000
5.0	0.9	1.67	2200
5.5	↓	2.15	2250
6.0	↓	3.27	3650
6.5	↓	5.4	4500
7.0	↓	5.2	4900
7.5	↓	6.4	4700
8.0	↓	6.67	5100
8.5	↓	7.8	4850
5.0	1.4	1.2	1100
5.5	↓	2.0	2250
6.0	↓	2.4	3650
6.5	↓	3.8	4800
7.0	↓	4.4	4500
7.5	↓	5.5	4250
8.0	↓	5.2	4000
8.5	↓	7.2	5800

Table 2 6512-02

V_N kv	P in. hg	I_T μ_a	$\overline{(Q/M)}$ coulombs/kg
5.0	0.4	0.31	940
5.5	↓	0.67	1425
6.0	↓	2.1	3650
6.5	↓	2.75	3400
7.0	↓	2.75	4500
7.5	↓	2.3	4200
8.0	↓	2.45	5000
8.5	↓	2.90	5000
5.0	0.9	0.5	1575
5.5	↓	2.1	2200
6.0	↓	3.0	3650
6.5	↓	3.9	3850
7.0	↓	5.5	4500
7.5	↓	4.5	3900
8.0	↓	5.5	4000
8.5	↓	5.2	4750
5.0	1.4	1.0	700
5.5	↓	1.9	1750
6.0	↓	3.0	3650
6.5	↓	4.0	2500
7.0	↓	4.1	3100
7.5	↓	7.4	3900
8.0	↓	[illegible].6	5000
8.5	↓	6.3	4850

Table 2 6512-02

V_N kv	P in. hg	I_T μa	$(\overline{Q/M})$ coulombs/kg
5.0	2.4	1.0	610
5.5		2.7	1200
6.0		2.5	1300
6.5		4.1	1900
7.0		4.9	2300
7.5		5.7	2550
8.0		9.0	3600
8.5		11.0	4700

In addition several runs were made with stainless steel capillary needles, 0.008 by 0.004 in. utilizing glycerol-NaI. The following observations are made:

a. Higher Q/M ratios are obtained in comparison with the standard platinum needle.

b. Greater etching of the steel needles occurs.

c. The 0.008 x 0.004 steel needles appear to arc and discharge more often than the larger Pt needles.

d. The stability of current flow is greater with use of the Pt needle compared to the steel needle.

Finally an 0.014 by 0.004 Pt needle was generated with a 90 degree I.D. tip. Although initial performance for 8 hours gave excellent results, after a continuous run of an additional 12 hours, the needle efficiency dropped and a glow was observed at the needle tip. Considerable ion emission was measured.

Microscopic examination revealed severe erosion of the capillary inside diameter rim. Normally this does not occur with a standard needle. It was decided to stop further testing with the 90 degree internal tip and to continue tests with the standard internal bevel tip.

4) Run 6604-09

A standard 0.014 by 0.004 polished beveled tip needle using glycerol-NaI, resistivity 4700 ohm cm, was put into operation. It was consistent and stable. It was allowed to run over the weekend unattended. During this time a ballast tube in the regulated power supply shorted out. Although the needle potential was fixed at 5 kv on a Friday, the potential read 8 kv on Monday and the needle tip was glowing. The voltage was dropped and the following data obtained using a 0.125 in. extractor aperture:

V_{xtr}	-300 volts
V_{spr}	-9 volts
V_{cone}	+45 volts
V_{screen}	+22 volts

Pic No.	p"Hg	V_N KV	I_N μa	$\overline{Q/M}$ c/kg
1	5	4.5	7	2800
2	5	5.7	15.5	6100
3	10	4.5	7.5	2100
4	10	5.7	18.5	5200
5	2.5	5.7	14.5	11000
6	2.5	4.5	5.7	4350

Figure 6 is a photograph of the T.O.F. traces produced at 5.7 kv and a number of pressures. The efficiencies are above 75 percent.

5. Run 6604-11

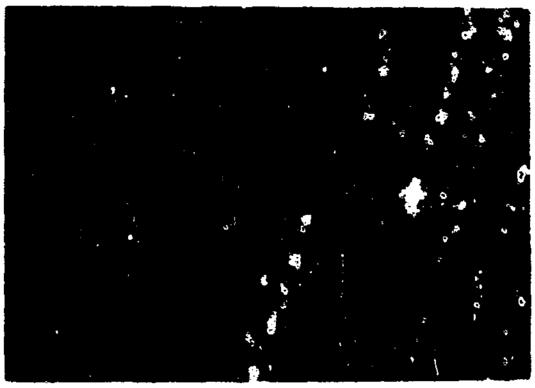
The same needle and fluid as used in the previous run, 6604-09, was remounted to look into an 0.093 in. diameter extractor aperture which is the same geometry used in the 60 needle module. The results are listed below

V_{xtr}	-300 volts
V_{spr}	-9 volts
V_{cone}	+45 volts
V_{screen}	+22 volts

Trace A

V_N 5.7 KV
P 2.5" Hg
I_N 14.5 μa $\overline{Q/M}$ = 11,000 c/kg
Sweep 5 μsecs/
2 μampc/

Trace B



V_N 5.7 KV
P 5.0" Hg
I_N 15.5 μa $\overline{Q/M}$ = 6100 c/kg
Sweep 5 μsecs/
2 μamps/

Trace C

V_N 5.7 KV
P 10.0" Hg
I_N 18.5 μa $\overline{Q/M}$ = 5200 c/kg
Sweep 5 μsecs/
2 μamps/

tor Distance 10 cm

Figure 6. Single Needle T.O.F. 6604-09, 0.125 in. Diameter Extractor Aperture.

Pic No.	p"Hg	V_N kV	I_N µa	$\overline{Q/M}$
1	2.5	4.5	6.75	5200
2	2.5	5.7	15.0	13,500
3	5.0	4.5	9.25	4950
4	5.0	5.7	18.5	8800
5	10.0	4.5	9.75	2300
6	10.0	5.7	23.0	5150

Figure 7 is a photograph of T.O.F. traces produced at 5.7 kv looking into an 0.093 extractor aperture at a number of pressures. It will be observed that efficiencies of the 0.093 extractor aperture geometry are somewhat lower than the 0.125 geometry, average charge/mass somewhat greater. Although both aperture geometries are in use, the 0.125 size is considered a more conservative choice and therefore preferrable at least for an ensemble of needles.

6 Single Needle Test 6605-02

A single platinum needle 0.0014 x 0.004 inches was sealed to the end of a glass tube and mounted within the 4 x 8 foot vacuum chamber. The propellant was NaI-glycerol, ρ = 4650 ohm cm. The fluid pressure was eight inches of Hg. The needle potential was six kv with a negative 300 volts on the extractor. The needle was permitted to run for 120 hours with no change in parameters. It was then terminated for a photomicrographic examination. The single needle current averaged out at 24 microamperes. The measured mass flow rate was 3.7×10^{-9} Kg/sec. This led to a calculated average charge/mass ratio of 6500 coulombs/kg. A flat T.O.F. collector 100 cm downstream was used to obtain T.O.F. traces. However the poor electronics coupled with the 30 inch diameter collector surface made meaningful efficiency results difficult to obtain. Since the goal in this run was to observe needle surface degradation, no attention was given to the charge/mass distribution.

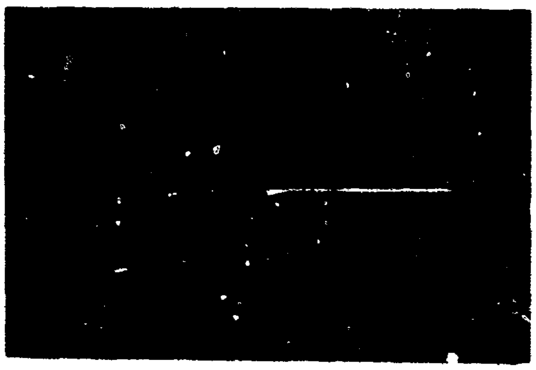
Trace D

V_N 5.7 KV
P 2.5"Hg
I_N 15 μa
Sweep 5 μsecs/
2 μamps/

Trace E

V_N 5.7 KV
P 5.0"Hg
I_N 18.5 μa
Sweep 5 μsecs/
2 μamps/

Trace F



V_N 5.7 KV
P 10.0"Hg
I_N 23.0 μa
Sweep 5 μsecs/
2 μamps/

Collector Distance 10 cm

Figure 7. Single Needle T.O.F. 6604-11, 0.093 in. Diameter Extractor Aperture.

Figure 8 is a reproduction of a photomicrograph made at 100X magnification after the 120 hour run. It should be observed that neither the interior bevel nor the needle tip show noticeable damage or wear. The uneven nature of the I.D., 0.004 inch, is interesting. Figure 9 of the same needle at 400X is of interest when contemplating a zero "g" surface tension feed system. The rough hump on the bevel set up in the coining operation used to generate the needle tip would impede or stop the propellant flow in a surface tension feed system.

7. Single Needle Test 6605-05

A single needle was mounted in the 4 inch Veeco station with a number of goals. These include the obtaining of beam current and average charge/mass ratio as a function of needle potential and feed pressure and the start of a life test. A four inch radius T.O.F. spherical collector was used to obtain meaningful T.O.F. traces. After the initial data was obtained the needle continued to operate at fixed values of needle voltage and propellant fuel pressure. The needle potential was held at 5.5 kv the fluid feed pressure was 5" Hg. The extractor was held at a negative 300 volts.

The test was terminated after 164 hours. During the last 24 hours of the run, it was observed that the needle current was fluctuating 10 percent and that the ion content in the beam had increased somewhat as shown on the T.O.F. traces. Some inquiry soon established the fact that the needle had run dry of propellant after approximately 100 hours of operation. For a period of hours (about 12) the needle had been running on air. Without turning the system off, the needle was refilled with propellant and run an additional 48 hours. When this fact was called to the attention of the program manager, the test was terminated and the needle inspected. A sharp beaded rim was observed along a small portion of the needle tip. Some representative T.O.F. traces were then transferred to IBM cards and released to the computer program for analysis. Section IX discusses this program. During the initial 100 hours the needle current averaged a steady 13 microamperes, the efficiency was 77 percent, the average Q/M ratio was 2600 coulombs/kilogram. After the needle was refilled (damaged rim) the efficiency dropped to 68 percent, the average charge/mass rose to 3800 coulombs/kilogram with a needle

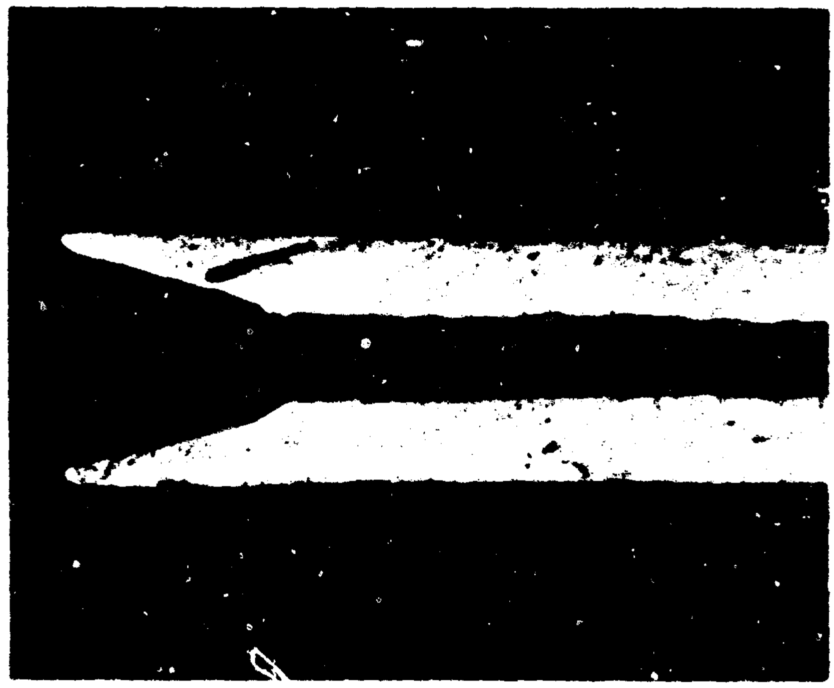


Figure 8. Needle Profile 100X.

Figure 9. Needle Detail 400X.

current fluctuating between 14 to 16 microamperes. On the other hand during the last hours of operation the efficiency could be increased to 81 percent by lowering the needle potential to 4.5 kv. The current was 12 microamperes, the average charge/mass 3800 coulombs/kilogram with the lowered needle potential.

Evidently the damage experienced by the needle in the flow discharge incurred by passage of air through the high potential capillary eroded the tip sufficiently to produce a low efficiency distribution (68 percent) after refilling. Of significant importance was the ability to improve the performance by decreasing the needle potential from 5.5 kv to 4.5 kv in spite of the damaged tip.

B. Physical Properties Measurements.

The physical properties of test liquids are now being measured as a regular part of the test program. The properties measured include viscosity, surface tension and density as well as the usual resistivity measurements. For the sodium iodide-doped glycerol normally used in charged droplet experiments (3 gm NaI:10 ml $C_3H_8O_3$) the following parameters have been measured for a typical batch at [illegible]°C; resistivity - 4650 ohm-cm, surface tension - 72.7 dyne-cm, specific gravity - 1.44, viscosity - 1260 centistokes. By way of comparison, the values measured for pure Baker Reagent Grade Glycerol were 2×10^6 ohm-cm, 66.5 dyne-cm, 1.261 and 850.7 centistokes respectively.

C. New Solutions

1) Sodium Ethylate Doping

Although unverified the possibility exists for a glycerol-NaI mixture to split apart in the spraying process leaving a negative iodine ion at the needle tip which would then become a neutral atom. With this in mind sodium ethylate was tried as a doping agent in a concentration of 11.84 grams to 450 ml glycerol. The chemical formula for sodium ethylate is C_2H_5ONa. Should splitting occur the C_2H_5O negative ion is soluble in glycerol. The physical properties of the solution were respectively

3470 ohm cm, 63.5 dyne-cm surface tension, 1.260 specific gravity, 1316.4 centistokes viscosity. Table 3 lists the single needle time of flight results obtained with the solution using a 1/8" aperture extractor plate. Feed pressure of the order of 10 to 30 "Hg were required to achieve steady operation.

The results indicated, by comparison with NaI doped glycerol, low charge to mass ratios (1000 or less), high thrusts (8 to 20 micropounds per needle) and beam efficiencies of the order to 75 to 80%.

2) Reduction of Surface Tension

The influence of surface tension on beam parameters was also investigated. Ten drops of Dowfax 9N9 Surfactant added to 450 ml of the ethylate solution reduced the surface tension to 34.6 dyne-cm. without measurable affecting the other parameters. Table 4 lists the single needle results subsequently obtained. The results indicated a lowering of efficiency and charge to mass ratio, a relatively unstable beam and no apparent beneficial results due to the lowered surface tension.

TABLE 3 - Run 6605-08 Sodium Ethylate-Doped Glycerol

Run	Voltage KV	Pressure "Hg	η %	Q/M Coul/Kg	Mass Flow Kg/sec $\times 10^{-7}$	I_{sp} sec	Thrust μ/lbs	Needle current μ amps
1	6.2	30	80.2	386	.386	200	17.1	15
2	7.0	↓	75.6	578	.371	252	21.2	22
3	8.0		78.9	1062	.273	373	22.2	29
4	7.5		74.4	842	.286	313	20.5	25
5	5.5		80.2	306	.394	167	14.6	12
6	5.5		78.3	475	.242	206	11.0	11.5
7	6.2		79.2	771	.197	281	12.3	15.25
8	7.0	↓	76.7	663	.316	272	18.9	21.0
9	5.5	15	78.7	536	.206	220	9.95	11.0
10	6.2	↓	80.5	749	.203	279	12.5	15.25
11	5.5	10	79.2	627	.167	238	8.8	10.5
TABLE 4 - Run 6606-02 Sodium Ethylate-Doped Glycerol + Dowfax 9N9								
1	6.2	30	71.2	373	.214	185	8.8	8
2	7.0	↓	74.3	344	.348	193	14.8	12
3	8.0		70.3	525	.286	248	15.7	15
4	7.5	↓	79.3	614	.212	275	12.9	13
5	5.5	30	73.7	248	.211	155	7.21	6
6	5.5	20	72.5	424	.094	187	3.91	4

3) NaOH + Glycerol

A solution of 2.16 gms of NaOH in 270 ml glycerine produced the single needle results shown in Table 5. The solution parameters were 7215 ohm cm resistivity, 66.4 dyne-cm surface tension, 1.255 specific gravity, 1023.6 centistokes viscosity.

The time of flight results (Table 5) were characterized by low charge to mass ratios, high beam efficiencies, thrusts as high as 17 micropounds for a single needle.

TABLE 5 - Run 6606-04 Sodium Hydroxide-Doped Glycerol

Run	Voltage KV	Pressure "Hg	η %	Q/M Coul/Kg	Mass Flow Kg/sec x 10^{-7}	I_{sp} sec	Thrust μ/lbs	Needle current μ amps
1	6	5	80.3	427	.664	207	2.94	2.75
2	7	↓	76.3	530	.753	243	4.04	4.0
3	8	↓	74.7	856	.614	326	4.41	5.25
4	9	↓	72.9	946	.690	359	5.43	6.5
5	10	↓	76.0	1009	.770	399	6.78	7.75
6	6	10	89.2	157	.770	132	1.21	2.25
7	7	↓	81.5	295	1.27	187	5.25	3.75
8	8	↓	73.9	516	1.02	252	5.65	5.25
9	9	↓	69.9	770	1.01	317	7.05	7.75
10	10	↓	70.0	871	1.10	356	8.60	9.5
11	6	20	95.5	102	3.17	110	7.75	3.25
12	7	↓	85.6	190	2.50	154	8.46	4.75
13	8	↓	79.6	297	2.18	198	9.55	5.5
14	9	↓	77.3	397	2.21	240	11.7	8.75
15	10	↓	75.2	542	2.12	291	13.6	11.5
16	6	30	90.0	114	4.4	113	11.0	5.0
17	7	↓	85.5	188	3.06	153	10.3	5.75
18	8	↓	83.7	216	3.28	173	12.6	7.1
19	9	↓	79.9	301	3.08	212	14.4	9.25
20	10	↓	77.8	372	3.16	245	17.1	11.75
21	6	20	83.5	264	1.22	166	4.52	3.25
22	7	30	82.1	283	2.03	184	8.25	5.75
23	9	30	77.1	545	1.70	280	10.5	9.25

IV MODULE DEVELOPMENT

The following section will describe a number of experiments performed with an ensemble of capillary needles. At present two modules have been constructed and are in use. One module can hold up to 37 needles in a hexagonal. Each needle is spaced 0.25 in. from an adjacent needle. The greatest distance between end needles is 1.5 inches. The 61 needles module covers the same area. Normally the full complement of needles are not used in a run due to the loading of the pumping station.

A. Six Needle Ensemble

1) Runs 6512-09, 10, 11

A 36 needle module containing six Pt needles and utilizing glycerol-NaI as a propellant fluid was tested in a 4 x 8 foot tank. Following a period of instability, fluctuations in current and efficiency, a run was made which started December 22 and terminated on December 28, 1965. The module was operated "full blast" for eight hours on December 22 and then throttled down. The "down" procedure was a decrease in the mass flow rate and needle potential so that the beam current dropped to 20% of its full value. Since the beam current for the six needles was normally 30-40 microamperes, the down current averaged 7 microamperes. Monday, December 27, 1965 the module was turned up full again and operated continuously for the next 32 hours. The test was then terminated in order to examine the needle tips.

A summary for the performance of the six needles follows:

a. I_{sp} = 4000 seconds
b. V = 6 KV
c. I = 40 microamperes
d. T = 2.74 micropounds
e. P = 0.24 watts
f. P/T = 87.5 KW/pound

The P/T ratio does not contain the efficiency of the distribution. From T.O.F. data this is estimated to be better than 75 percent. The peak distribution of the Q/M ratio was 130,000 coulombs/kg.

An attempt was made to lower this astronomical figure by decreasing the extraction potential and increasing the mass flow rate. However the module seemed to prefer, in terms of stability, the high charge/mass peak. The needles used for this run were freshly prepared in thin rim capillary Pt tube, 0.014 by 0.008 inch, stuffed with Pt wire. The resistivity of the glycerol-NaI solution was ≈ 5700 ohm cm. It was noted however that in transferring the glycerol "under vacuum" to the module reservoir a large number of gas bubbles entered the fluid. At the conclusion of this run, the needles were examined. All of them contained polymerized glycerol around the rims of the tubes. In spite of this surprising turn of events, operation was smoother than usual.

2) Run 6601-01

Six stuffed needles (0.014 by 0.008 inch) were used in the module for a three hour run with 5100 ohm cm NaI. Q/M peaks in excess of 10,000 coulombs/kg with total currents from 50-60 microamperes were obtained. Efficiencies are estimated as greater than 70 percent as obtained from T.O.F. traces. Examination of the needles following this brief run showed them to be clean.

3) Run 6601-03

The second six needle run (same needles as previous run) was made with H_2SO_4 instead of NaI. The resistivity at 25°C was 1740 ohm cm. This run was permitted to proceed for 94.25 hours continuously and at "full blast". It was terminated only out of boredom. During this test the shield, just downstream of the extractor, was temperature monitored with a thermocouple. With the LN_2 cold wall in operation, the shield and very likely the module dropped from 21.75°C at the run start to 15°C 3.25 hours later. Total currents of approximately 80 microamperes were obtained with Q/M peaks running from 4000 to 9000 coulombs/kilogram. Efficiencies were 75% or better. Once again it was observed that glycerol-NaI beam currents are more uniform than beams emitted from glycerol-H_2SO_4.

4) **Run 6601-06**

This was the first run made with the new high density module. This module, identical in size with the standard module, has provisions for higher density needle packing. Although only six needles were used, this module is capable of containing 61 needles in contrast to the 37 needles of the standard module. The module used with 5100 ohm cm NaI (as in test 6601-01) appeared to operate satisfactorily although Q/M peaks >100,000 C/Kg were obtained. The same fluid was then tried out on a single needle and observed to have the same very high ion content. It was concluded that the new module could be used.

5) Run 6601-11

The high density module containing six needles and 4690 ohm cm NaI was allowed to run continuously for three days and throttled operation for two nights. Q/M peaks were held to 4000 coulombs/kg. A range of currents extending from 60 microamperes to 100 microampere beams was obtained by manipulating needle voltage and feed pressure.

6) Run 6603-01

A run extending over a period of 72 hours was made with the low density module containing six needles, 0.014 by 0.004 in. The propellant used was glycerol-NaI, $\rho \approx 4700$ ohm cm. Figure 2 is a graph of thrust (micropounds) vs beam current (microamperes). The needle potential was varied between five kilovolts and seven and one half kilovolts. The average slope is approximately 0.4 micropounds per 1.0 microamperes. This figure of merit does not include either the mass flow rate efficiency or beam divergence effect.

Figure 3 represents the same data for which thrust is plotted against the I_{sp}. Also shown on this graph are the isopotential lines.

7) Run 6605-07

This run was made with the low density module facing an 8 inch radius T.O.F. spherical collector. Six needles were mounted in the first ring of the 37 needle module. The capillary tube potential was held at 5 kv, the extractor at a negative 300 volts and the fluid pressure at 2 inches Hg. The glycerol-NaI propellant has a resistivity of 4650 ohm cm. T.O.F. traces were taken every hour of the working day. On evenings and weekends, the six needle module ran unattended. No cryogenic wall was used, the tank pressure held at 8 x 10^{-6} torr. No attempt was made to hold the module temperature constant. The temperature (21.5°C) was measured at various times during the run and was found to be constant within a few tenths of a degree. The fluid pressure, 2" Hg, was dependent upon the atmospheric pressure and could therefore vary a few percent.

The run was operated for a total of 172 hours of continuous duty with 169 hours at the parameter given above. The run was then terminated in order to initiate a new run with a full complement of 37 needles. The needles showed no wear. However some staining was observed on the side of the needles. In addition the extractor electrode was heavily wetted with a deposit of condensed glycerol. No extractor current was observed (< 0.1 microampere). Eleven representative T.O.F. traces taken at the start and conclusion of each working day were placed into the computer program for analysis and are listing in the table following. The column marked T_c is the thrust incident upon the collector surface. ΣT is the total thrust ratioed from T_c using needle current.

Date	Time	I_N μa	η %	T_c μlbs	I_{sp} sec	Q/M coulombs/ kilogram	ΣT μlbs	I_N/ΣT μa/μlb
5-24	1200	90	82	6.86	708	5861	24	3.75
5-24	1700	86	73	5.42	701	6485	20.5	4.20
5-25	0830	85	80	7.07	572	3946	27	3.15
5-25	1700	69	79	5.45	556	3786	22.4	3.08
5-26	0830	76	80	5.49	573	3944	24.4	3.11
5-26	1700	66	78	5.34	502	3125	23.3	2.84
5-27	0830	79	78	4.37	563	3921	25.0	3.16
5-27	1700	70	79	4.91	560	3799	22.8	3.07
5-29	0830	84	74	6.36	511	3390	28	3.00
5-31	0900	80	76	6.90	381	1641	36.6	2.19
5-31	1300	68	80	4.79	470	2650	26.5	2.56

The results for the most part are reasonably encouraging. However runs of much longer duration will be necessary if changes with time are to be made apparent. The specific impulse and thrust columns are corrected for efficiency loss. The current per unit thrust gives an average value of 3.1 microamperes per micropound.

B. Beam Profile

A high density module containing six needles and using 4690 ohm cm glycerol-NaI was permitted to operate continuously with no throttling for 100 hours (6601-12).

A 0.75" diameter shielded probe with a suppressor grid held at a negative 45 volts at a nominal center line distance of 18 cm from the module was used to explore the distribution of current emitted. Figure 10 shows the geometry of the experiment. The probe was centered with respect to the module. It was then pulled out in increments of 0.75 inches. Only the probe collector current was used for calculations in order to avoid secondary emission effects from other portions of the probe structure.

PROBE GEOMETRY HIGH DENSITY MODULE,
6 NEEDLES 3/16 INCH SPACING, 2 NEEDLES SHOWN
RUN 6601-12, 1/24/66

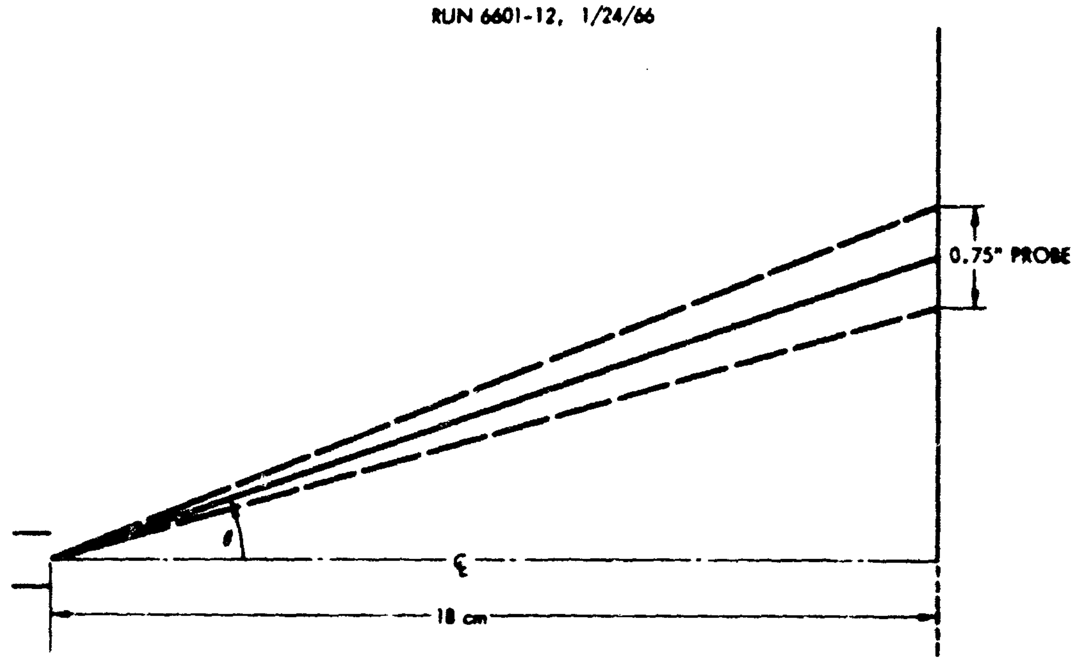


Figure 10. Probe Geometry.

PERCENTAGE CURRENT INCLUDED WITHIN HALF ANGLE θ

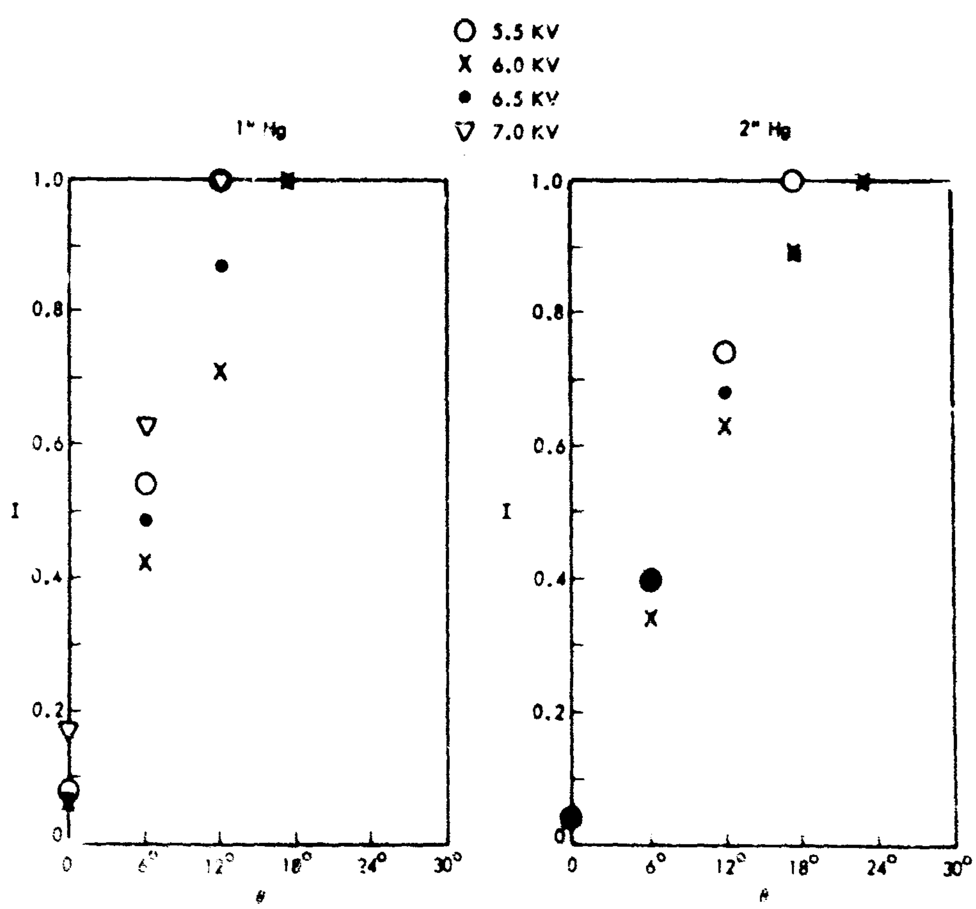


Figure 11. Probe Results 1" and 2" Feed Pressure.

The probe current at each half angle setting θ was then multiplied by the total annular area corresponding to the position of the sampling probe. For each needle voltage value and feed pressure a normalized current was obtained for the total field. The normalized current percentage I was then plotted against the half angle position of the probe. Figure 11 contains the data for 1-inch Hg feed pressure and 2-inches of Hg feed pressure. To help interpreting the graphs consider the 1-inch Hg feed pressure. At an extractor voltage of 6 KV, 75 percent of the total current emitted from the 6 needles is contained within a half angle of 12 degrees or a total cone of 24 degrees However at extraction voltage of either 5.5 or 7.0 KV, 100 percent of the emitted current is contained within a half angle of 12 degrees. The worst case is shown in Figure 12 for 4-inches of Hg feed pressure. At 6.5 KV the beam profile extends to 32.5 degrees half angle. The data obtained with 3 inches and 4 inches of propellant pressure are shown in Figure 12.

C. <u>60 Needle Module</u>

A number of runs have been made with the 60 needle module and glycerol-NaI (approximately 4700 ohm cm). At the present time the performance of the 60 needle module is undistinguished due to the arcing at currents greater than 300 microamperes. A great deal of attention is being given to this problem. It should be noted that single needles do operate with similar geometry and regularly produce between 10 - 15 microamperes with little or no arcing. During one of the experiments mentioned above, the module was operated at 700 microamperes for about an hour. During this time severe intermittent arcing was observed. However a microscopic examination of the needles after the run showed no damage to the 60 needles. During the run, the room was darkened in order to observe the relatively sharp emergent beam. In addition the collection volume bounded by the cold walls was found to emit light in a manner reminiscent of the 100 kv runs.

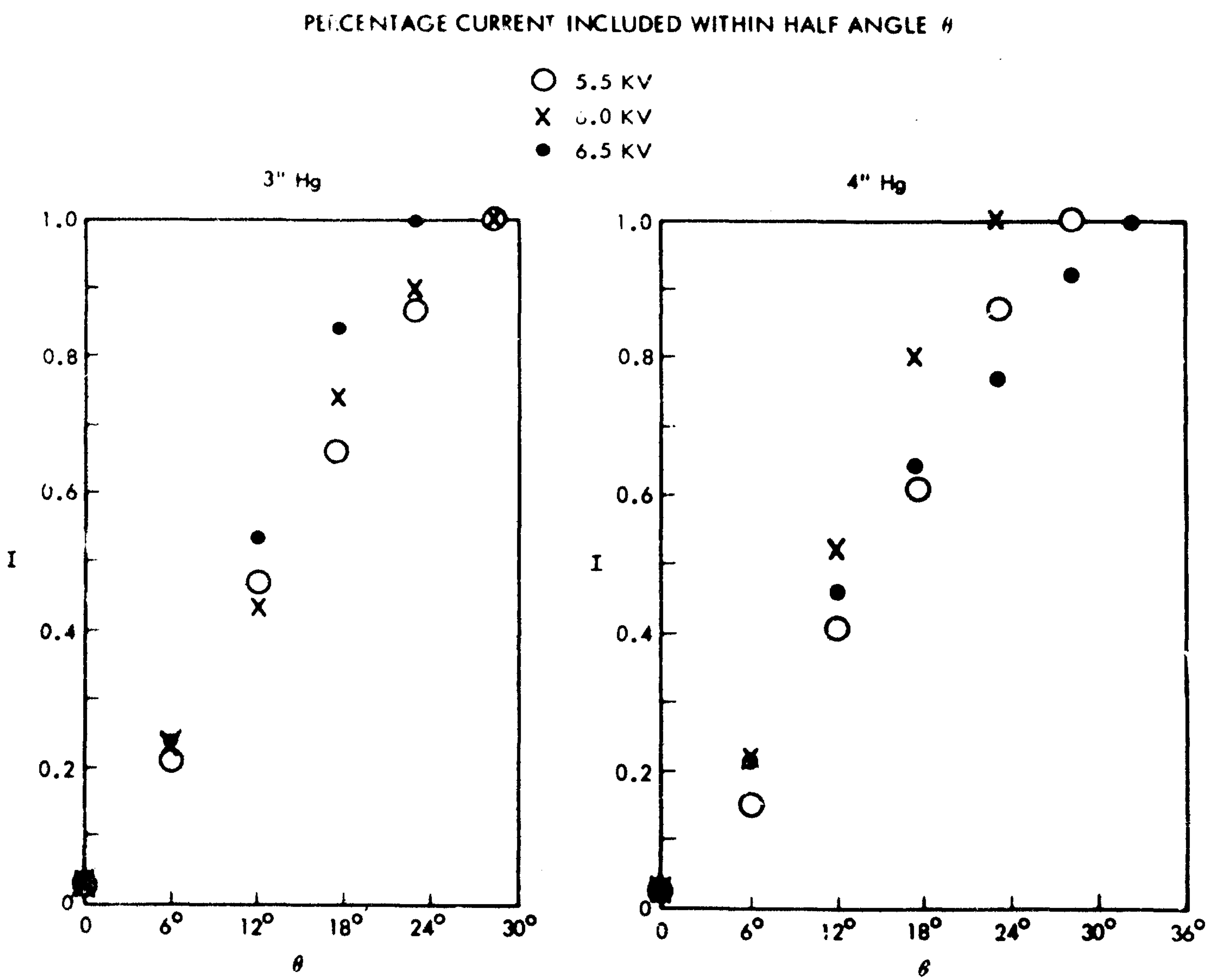


Figure 12. Probe Results, 3" and 4" Feed Pressure.

Figure 13 is a photograph of three T.O.F. traces made during run 6604-08. System parameters are listed below:

V_N	5 kv
P	0.1 inches Hg
I_N	90 microamperes
Collector distance	100 cm
Trace A	50 microseconds/cm, 5 microamps/cm
B	5 microseconds/cm, 5 microamps/cm
C	2 microseconds/cm, 5 microamps/cm

It will be noted that the initial flat portion of the curve is 13 microseconds in duration. A charge/mass ratio of 590,000 coulombs/kilogram results. The slowest arrival time is 190 microseconds or 2800 coulombs/kilogram. Since the T.O.F. collector is flat rather than spherical a difference of 12 percent is possible in q/m determination for a particle arriving on axis over the same particle striking the periphery of the collector. Trace B also shows a second ion species is present. Two molecules of glycerol with a single positive charge produce a charge/mass ratio of 520,000 coulombs/kilogram. It is not possible at this time to identify the ion peaks obtained as two molecules of glycerol. About 42% of the beam current is produced by the ion for this particular run. Additional data concerning the high density module will be found below and in Section VI.

D. Gas Analyzer

The formation of H_2 and CO other than glycerol vapor as principal causes of pressure rise during thrustor operation is discussed here. It should be stressed that these two gases appear to be the principal offenders in the mass range from 1 to 70 amu.

A quadrupole gas analyzer was mounted through a port and extended directly into the vacuum tank. For this run, scanning was electronic and read out by means of a Varian recorder.

Trace A

V_N	5.0 KV	
P	0" Hg	
I_N	90 μa	
Sweep	50 μsecs/	
	5.0 μamps/	

Trace B

Sweep 5.0 μsecs/
5.0 μamps/

Trace C

Sweep 2.0 μsecs/
5.0 μamps/

Figure 13. 60 Needle Module T.O.F. Trace, One Meter Collector Distance, [illegible].

Prior to turning on the colloid beam, the tank pressure was 2×10^{-7} torr, LN_2 cold wall in operation. The mean peaks were 18 (water vapor) and 44 (CO_2) and were emitted from the analyzer walls. This was shown by the drop in chamber pressure from 1×10^{-5} torr to 2×10^{-7} torr when LN_2 was pumped into the cold wall. During this time the two peaks remained nearly constant. Only a trace of 28 (CO) was present and no H_2 was detected. With the multimolecular beam on, the chamber pressure rose to 2×10^{-5} torr. The dominant gases of 28 (CO) and H_2 were now observed.

The gas analyzer has two ranges extended from 1 to 4 amu and 5 to 70 amu. The sensitivities on these two ranges differ. The ratio of partial pressures could not be determined from peak heights during this run.

RUN 6603-07
3-29-66

60 Needle Module
Module Temp. 25°C

$\rho \approx$ 4700 ohm cm
Glycerol-NaI

GAS ANALYSIS DATA

Time	P " Hg	V_N kv	I_N μa	Chamber p torr	1-4 amu H_2 Peak *	18(a)	28(b)	44(c)	Time
						Mass Range 5-70 amu			
13:40	0	0	0	$3x10^{-7}$	0	7.7	0.3	2.6	13:40
14:06	0	0	0	$2x10^{-7}$	0	6.7	0.2	1.9	14:06
14:40	1.0	6.0	500	$1.6x10^{-5}$	0.5	3.4	7.9	2.3	14:35
14:50	1.0	6.0	500	$1.6x10^{-5}$	0.4	3.3	7.8	1.9	14:45
15:15	1.0	6.5	650	$1.7x10^{-5}$	0.8	1.9	8.0	0.5	15:20
15:25	1.0	6.5	650	$1.5x10^{-5}$	0.7	1.7	7.9	0.5	15:30
15:32	0.5	6.5	405	$9.0x10^{-6}$	0.4	1.3	5.2	0.3	15:40
15:50	0.5	7.0	460 to 500	$1.0x10^{-5}$	0.4	1.4	6.3	0.8	15:55
16:00	2.0	6.0	650	$1.9x10^{-5}$	0.8	1.0	8.4	1.2	16:15

* Full Scale 10

(a) 18 peak most likely water vapor

(b) 28 peak most likely CO with the possibility of nitrogen

(c) 44 peak probably CO_2

Many minor peaks appeared once the beam was turned on. These occured at 12, 13, 14, 15, 16, 17, 22, 26 and 40 amu. No peaks were evident between 44 and 70 amu.

V. 100 KV POST ACCELERATION

A. High Voltage Testing

Notwithstanding the fact that post acceleration of a heavy particle beam is necessary to obtain specific impulses above 1000 seconds, only the first quarter of the year was given over to the relatively new and difficult task. The initial work on 100 kv acceleration was based upon obtaining an I_{sp} of 2000 seconds when a Q/M ratio of 2000 coulombs/kilogram beam was available. Recent work indicates that a higher Q/M ratio may be realized. Thus a beam with an average charge/mass ratio of 4000 coulombs/kilogram demands an acceleration of 50 kv in order to maintain the I_{sp} at 2000 seconds. A discussion of the trade-offs will be found in Section X.

At the start of the present contract, 15 July 1965, the maximum duration of a 100 kv run was two hours. Accel drain currents and X-ray emission were present even in a dry system, i.e. with no propellant delivered to the needles. A considerable improvement was made in the present program by replacing the teflon support rods between the accel-decel electrode system, operating at a negative 15 kv and the positive 100 kv module electrode with stainless steel supports extending from a ground potential region to the ground potential decel electrode. Arcing and discharges were eliminated in the dry system with this charge. Following this change in support geometry, four high voltage runs were made within a six inch pumping station. The duration of these runs extended from a two hour run to a five hour run.

Common to all of these runs was the rise in chamber pressure from 1×10^{-6} torr or lower just preceding droplet emission to a final pressure at termination of 2×10^{-4} torr. The emission of x-radiation followed this pressure change. When the 100 kv supply was turned off, the pressure dropped by a factor of ten immediately. The ability to increase the duration of the high voltage runs to two hours and greater made it possible to obtain more reliable data and to begin removing superfluous or redundant elements such as shields or electrodes from the system.

The ability to obtain 100 kv runs exceeding two hours as a routine matter in the six inch pumping station had greatly encouraged the colloid group and permitted a certain amount of optimism to prevail. During the period of time from October 4 to October 26, 1965, 9 runs were made at needle voltages of 100 kv and beam currents in excess of 100 microamperes. The final run described below was terminated after running continuously for eight hours. An average charge/mass ratio of $\approx$ 500 coulombs/kilogram was determined for each run from mass flow rate measurements. This rather low value together with modest beam currents averaging 125 microamperes should be compared with the 100 hour module test (no acceleration) which produced a beam of 260 microamperes at 2000 coulombs/kilogram under similar extraction conditions prior to the present contract. The same 36 capillary needles and been used continuously since March 1965. With the exception of cleaning operations the needles have been untouched. During this period, the thin rim needles have gradually been rounded off as demonstrated by examination with a microscope. By reworking the needle tips or generating new thin rims it was expected that both Q/M and beam current would be appreciably increased. This was verified by the subsequent work described in Section III and IV. It should be further kept in mind that all of the work described in this section was performed using a glycerol-H_2SO_4 propellant. This mixture produces a lower beam current and average charge/mass ratio than glycerol-NaI.

The nine runs are listed below. The module temperature was obtained immediately following the run termination by means of a thermocouple immersed in the fluid feed tube and situated just back of the module. The fluid used had a resistivity at room temperature of $\approx$ 2000-2500 ohm cm. The resistivities tabulated were measured at the conclusion of each run. The last column called "Geometry" identifies the downstream collection volume and is discussed further along in this section.

Date	No.	Life Hours	Temp °C	Resistivity	Geometry
Oct. 4	6510-01	4.25	51	400 ohm cm	hot wall collector
7	6510-02	3.0	62	325	hot wall + nose cone
8	6510-03	2.75	40	705	cold wall
12	6510-04	3.0	40	705	cold wall + nose cone
13	6510-05	4.0	40	1400	cold wall + baffle
18	6510-06	3.5	48.8	630	cold wall + new baffle
19	6510-07	4.0	49	610	cold wall + new baffle
22	6510-08	7.0	57.5	355	cold wall + new baffle + reservoir
26	6510-09	8.0	63	340	cold wall + new baffle + reservoir

The last two runs were made under nearly identical conditions with two exceptions. Run 08 of duration 7 hours, had a vacuum reservoir mounted within the high voltage two foot diameter sphere. This reservoir was used to decrease the mass flow rate of fluid propellant in order to keep the beam current relatively constant. This was accomplished by bleeding off the initial 3 inches of Hg air pressure forcing propellant through the capillary needles. When the vacuum reservoir and fluid pressure become equal after seven hours, the run was voluntarily terminated. The need for the mass flow rate and hence forcing pressure control was evident from previous runs by the increase in $\dot{M}$ with time which was occurring because of the rise in temperature of the module. This rise in temperature may be due to electron bombardment and/or an electrolytic reaction in the fluid, a matter to be investigated and a solution to the problem found.

The capacity of the vacuum reservoir was doubled for run 09. In addition, two adjacent electron structures, the focus electrode at 100 KV and the "accel" electrode at ground potential were not cleaned and polished (for the first time) but reinserted "dirty" for run 09. The run was terminated voluntarily after 8 hours, some arcing during the last hour and a certain amount of operator fatigue. The average mass flow rate appeared to be $\approx$ 1×10^{-7} Kg/sec. Using a conservative value of beam current of 125×10^{-6} amperes gave an average Q/M value of 800 coulombs/kilogram.

Figure 14 is a graph showing the pressure in the vacuum chamber and the radiation measured 16 inches distant from the center of the needles to the center axis of the radiation chamber as a function of time. The arrows indicate the times at which the forcing air pressure upon the fluid was changed in order to keep the beam current relatively constant.

Figure 15 is a plot of the supply current, I_{supply}, and the beam current I_{needle} as a function of time. Arrows again indicate the times at which the forcing pressure was changed. Attention is called to the relative flatness of all of the curves as a function of time. Similar curves generated previously had shown a continuous increase for all values with time whether current, pressure or radiation.

B. <u>High Voltage Conditioning</u>

The high voltage thrustor system was always conditioned dry, that is with no propellant fluid permitted to enter the capillary needles. The conditioning procedure consisted of raising the needles and focus electrode to 125 KV with the extractor plate 5 KV below this. With LN_2 in the cold wall, the needles were then lowered to 115 KV with the extractor at 100 KV. At this stage there should be no accel drain, < 0.5 μa, no visible glow or discharge of the electrode structures in darkness, and zero X-radiation < 0.5 MR/Hr. With these conditions met, voltages were lowered to operating levels, 100 KV on needles, 95 KV on extractor and propellant was introduced to the needles.

In arriving at these criteria for proper conditioning of zero accel current, zero flow, and zero X-radiation, three rather interesting modes were observed.

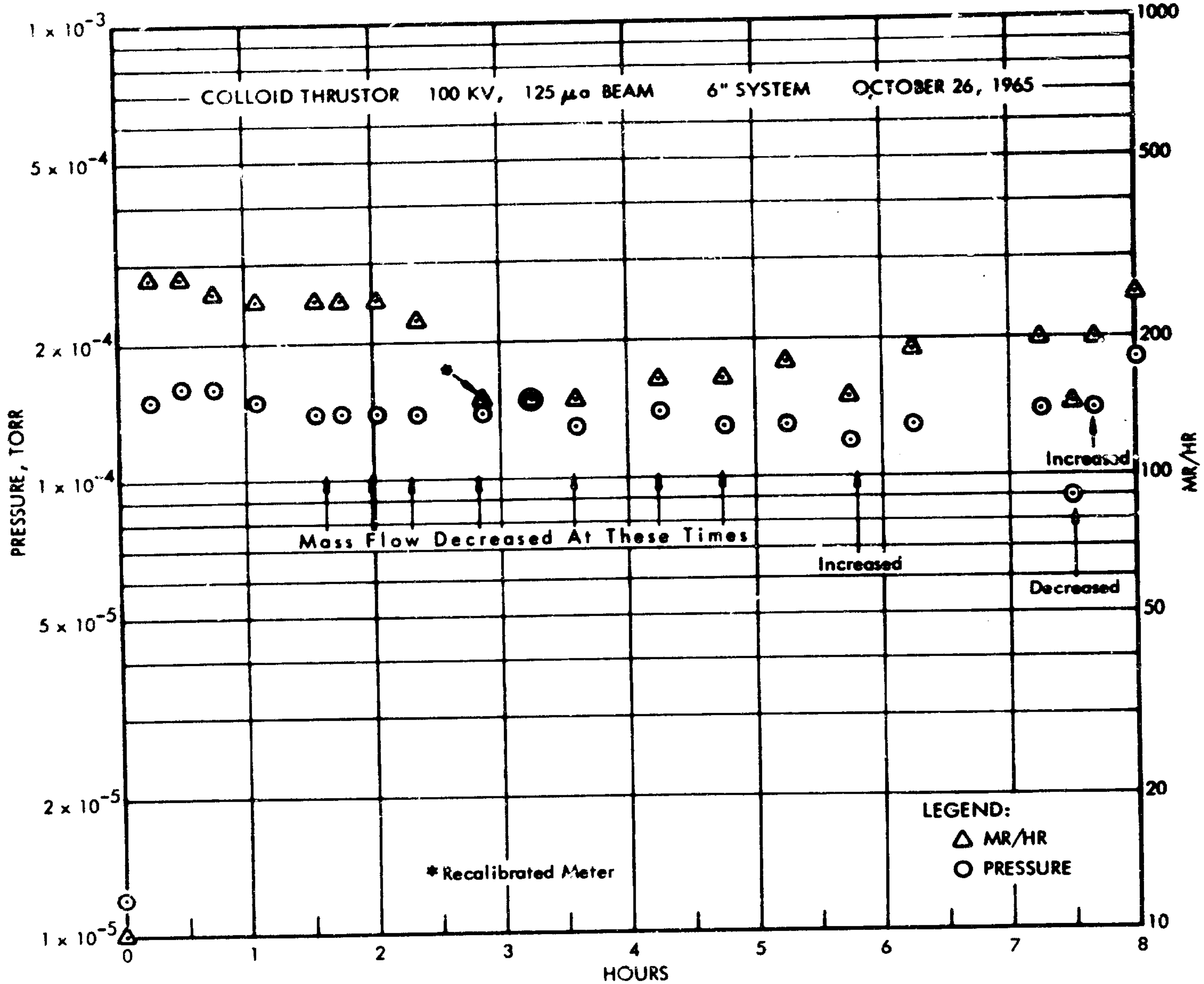


Figure 14. 100 KV Acceleration, Pressure and Radiation vs Time.

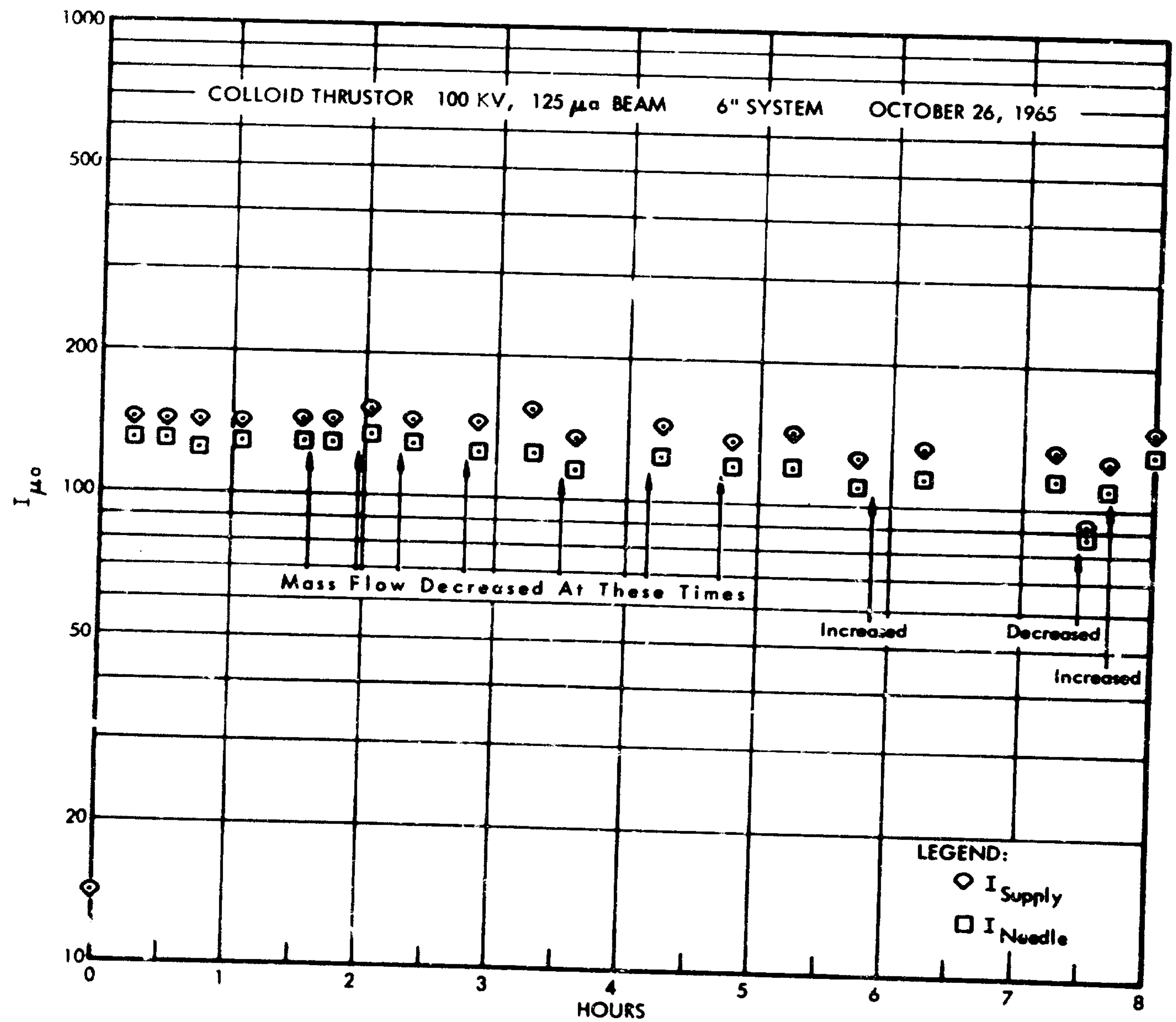


Figure 15. 100 KV Acceleration, Beam Current vs Time.

Mode 1. This mode is described above. It is a surprisingly stable mode. Chamber pressures may be varied from 2 x 10^{-7} torr up to 5 x 10^{-4} without disturbing the three zero levels. Indeed the pressure can even be raised to the mm range (with voltage off) and then lowered again to the 10^{-6} torr range by pumping and still remain in the Mode 1. Once Mode 1 is obtained, the cold wall may be warmed up to room temperature without leaving Mode 1.

Mode 2. This mode is also steady and is obtained in a dry state. With the high voltages described above but no LN_2 in the cold wall the following conditions are observed; an accel drain of ∿ 5.0 μa seemingly consisting of an electrode current from the grounded accel to the positive high voltage region or positive ions returning to the accel from the high voltage electrodes, a steady glow or discharge barely perceptible in darkness and confined to the region between accel and focus electrode accompanies the current drain, and finally an X-ray emission of 500 - 1000 MR/Hr as monitored 16" distant. This mode has been observed to run stably for hours and seemingly has no time limit. However should the pressure be raised sufficiently > 5 x 10^{-4} torr, a visible glow discharge will occur with subsequent breakdown and high radiation emission > 2500 MR/Hr.

Mode 3. This mode oscillates stably between 1 and 2. The period of oscillation is several seconds and shifts by itself from 1 to 2 and then extinguishes back to 1. Accel drain current thus alternates from zero microamperes to ∿ 5 microamperes. The glow appears and disappears. Along these two parameters the X-ray radiation stays in phase.

During a wet run of the thrustor accel drain and X-ray emission occur but no visible glow. The visible glow (in room darkness) appears near the termination of a run.

C. Whiskers, Oxides, Monomolecular Films, Poisons, Etc.

Some theorizing has resulted in an attempt to explain the above three modes. Originally it was thought that accel drain current or its equivalent, a low level visible glow and X-ray emission always accompanied

100 KV apparatus. It was only because operators of x-ray or electron diffraction apparatus never got their heads close enough to observe the glow and emission that it might be unreported. It is assumed that the users of such equipment would turn up the high voltage electrodes leaving the electron source off and then monitor drain, visible glow and x-ray emission. However this may be, the ability to condition our system to zero current drain, light and x-ray emission stopped this line of thought.

Discussion in the laboratory then centered upon poisoning of the accel-focus electrode structures giving rise to Mode 2. In some unknown fashion either whiskers appeared, oxide coatings, insulating films, and/or monomolecular layers of hydrocarbons, detergents or silicone pump oils were deposited upon the seemingly clean polished surfaces. In some equally mysterious fashion the surface was purged of these contaminants and successfully dropped to Mode 1. Mode 3 was not explicable, it only existed.

For the reasons given above all high potential surfaces as well as surfaces adjacent to high voltage regions principally the accel are carefully cleaned and polished before each run. However, following the seven hour run 6510-08, the focus electrode and accel were removed and not cleaned or polished. They had visible films on them. All of the other elements were cleaned as usual and all remaining high voltage surfaces polished. The system was assembled and an attempt was made to condition the thrustor into Mode 1 with the poisoned focus and accel electrodes. It was thought that if whiskers, oxides or monomolecular layers prevent proper high voltage conditioning then certainly these conditions should be present in the two electrodes untouched after a seven hour run. The radiation level at the conclusion of this previous run had been 300 MR/Hr with an accel drain of 13 microamperes.

It was found that the system was readily conditioned into Mode 1 with the "dirty" focus-accel electrodes. In fact run 6510-09 then ran successfully for eight hours. However it did appear that somewhat more arcing was prevalent than in the previous seven hour run.

D. <u>Collection Volume Geometry</u>

1) The accel was originally held at a potential of negative 20 KV. It was found experimentally that an appreciable improvement resulted from holding the accel at a negative 7 KV. This was the lowest potential for an efficient electron barrier. A less negative potential permitted electrons to pass into the high voltage region. A more negative potential drew positive charge from the collection area producing secondary electrons which would in turn see the high voltage electrodes. Finally a more efficient trap was generated at a negative 1500 volts by an additional electrode just downstream of the accel-decel configuration which is now held at ground.

2) The possibility existed that should the primary beam strike a clean metal surface somewhat more controllable results would occur. In order to accomplish this an optically opaque wall was fabricated which fitted within the LN_2 cold wall. This copper collector was then held at 100°C during a run. The beam would strike the hot clean surface give up its charge and then be scattered to condense on a cold wall with little energy. This occurred in run 6510-01. The run was relatively good. However a large amount of copper was sputtered upstream onto all electrodes.

3) A nose cone made of concentric cones was fabricated in an attempt to prevent scatter to the upstream region. To a first approximation the beam appears to originate from a virtual object point. Little or no improvement resulted.

4) Run 6510-05 was made with a baffled aperture between the electron trap and cold wall collector. This appeared to be a cleaner run in terms of copper backscatter. Examination of the baffle showed some direct interception.

5) For runs 6510-06 and on, a new baffle aperture was used which produced no direct interception and a minimum amount of back-scatter.

E. Visible Radiation Within Volume Included by Cold Wall and Honeycomb Collector

Although a visible glow or discharge may arise between the focus electrode and the accel either at the termination of a run or in a Mode 2 preconditioning period, a glow or discharge in the beam can be observed (in room darkness) from the start of a run extending from the exit of the decel electrode and throughout the collection volume. This low intensity glow or discharge may be conveniently observed through a viewing port in the cold wall. In order to learn something of the nature of the emitting gases involved, a monochromator with a photomultiplier detector was set up to view the light emission. Since the color of the light is blue, scanning was confined to the spectral region between 4000 and 5000 angstroms. The very low level of radiation demanded that a wide slit be used. In this spectral region five lines or bands were obtained centered at the wavelengths listed

4307 Å
4340
4728
4755
4860

At present the resolution of the monochromator cannot be increased in order to identify the gases involved. It is intended to use a mass spectrometer for this purpose in the future. Section IV describes the results obtained for a run with no post acceleration.

F. A Few Preliminary Conjectures Regarding Thrustor Life

Some evidence has been obtained based upon previous high voltage runs that noncondensable gases may form. The inability to exhaust these gases (in our six inch station) has contributed greatly to the problem of laboratory life testing. It is anticipated that while the new tank will improve pumping speed materially, the noncondensable gas problem will not disappear. The use of a gas analysis spectrometer should help in at least identifying the culprits. However it may be necessary to have a differential pumping system using a liquid helium wall for cryogenic pumping in the vicinity of the high voltage surfaces to alleviate the problem completely. The expense involved in this could be considerable.

IV. HEAVY PARTICLE NEUTRALIZATION

Self or autoneutralization of charged ion or heavy particle beam occurs normally in an earth bound environment. Sufficient secondary electrons will be emitted in a test vacuum station to permit a plasma to exist. In addition the ion engine people have developed and demonstrated the ability to neutralize an ion beam by injecting electrons into the beam. Until the present effort no work is known in which neutralization of a heavy particle beam had been accomplished by the injection of electrons.

A. Immersed Hot Wire Electron Emitter 6602-09

The schematic shown in Figure 16 illustrates the instrumentation for the experiment involving the neutralization of a heavy particle charged beam of positive particles by means of an immersed hot wire electron emitter. The 67 volt firing voltage neon lamp between collector and ground acted as a safety precaution. The 22 volt cell positive bias on the neutralizer was used only for convenience. The collector potential when floating rose five volts over the neutralizer bias. It would appear that neutralization of the beam was accomplished. Needle potentials from 6.0 to 7.5 kv were applied along with feed pressure from 1.5 to 2.5 inches Hg. The 60 capillary tubes in a high density module were 0.014 x 0.004 in. Pt. The glycerol-NaI resistivity was $\approx$ 4700 ohm cm. The heat radiated from the neutralizer filament raised the module temperature to 29.5°C with no LN_2 in cold walls. An additional run made with coolant in the cold walls led to essentially the same resultant degree of beam neutralization.

In the raw data listed below, calibration of the I_N meter shows it to be 10% low; the I_c, I_{Neu} and I_T meters are less than 5% high.

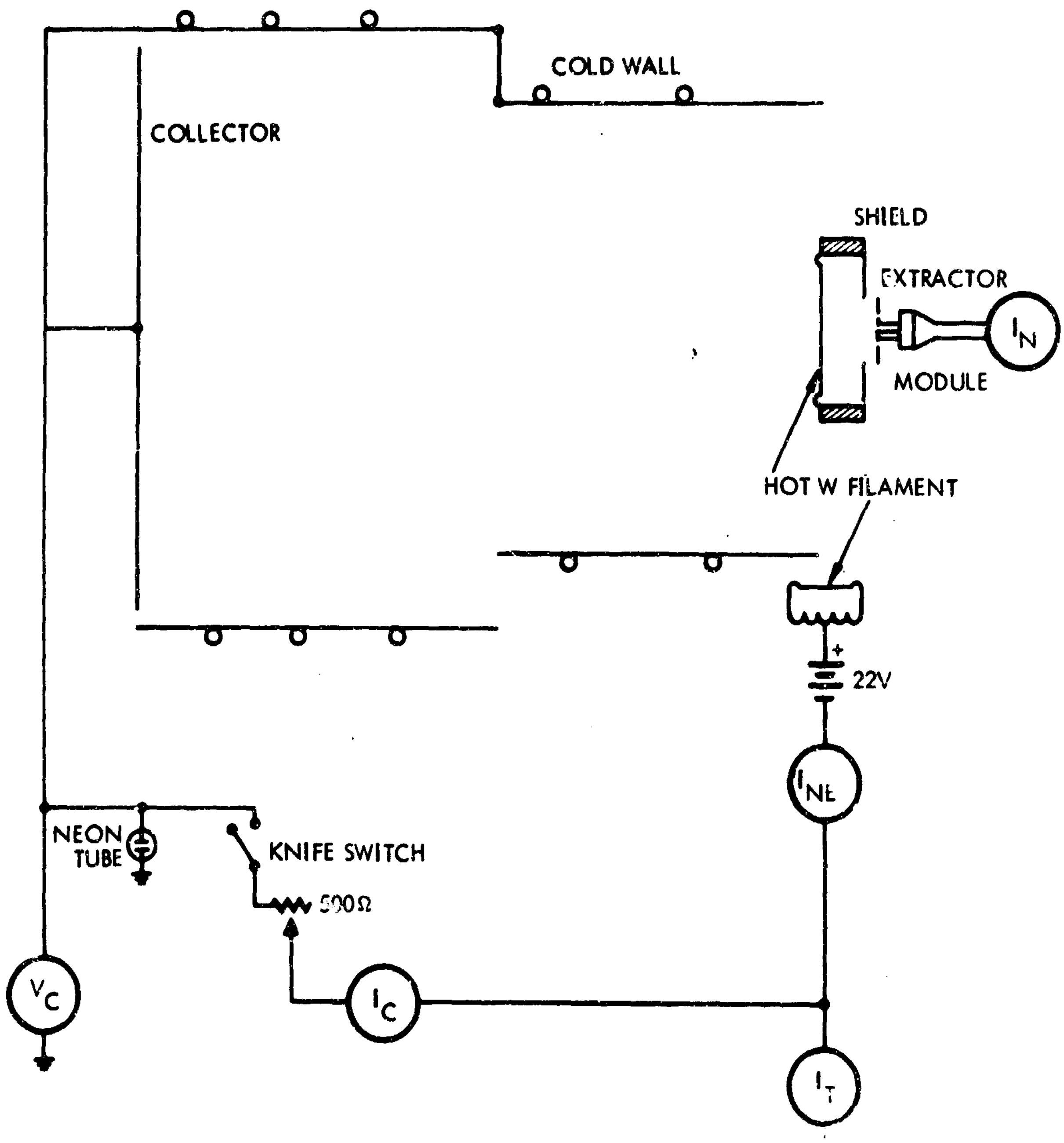


Figure 16. Schematic, Neutralization Equipment.

LN_2 in both cold walls.

P "Hg	V_N kv	I_N μa	I_c μa	I_{Neu} μa	I_T μa	I_{xtr} μa	I_s μa	V_c v	Switch Open 0 Closed C	Heater Setting Variac
1.5	6.0	215	0	220	220	.3	.5	26	0	124
	6.0	215	220	0	220	.9	2.5	5	C	
	6.5	260	0	280	280	.5	1	25	0	125
	6.5	260	280	0	280	1	4.5	6	C	
	7.0	400	0	440	440	1	2.5	29	0	125.5
	7.0	400	440	0	440	3.8	4.8	9	C	
	7.5	510	0	610	610	2	5	27	0	125.5
	7.5	510	610	0	610	2.5	3.5	7	C	
2.0	6.0	390	0	420	420	1	2.2	28	0	125
	6.0	390	420	0	420	1.8	4.8	8	C	
	6.5	460	0	470	470	1.2	3.5	26	0	125
	6.5	460	470	0	470	2.5	6.2	6	C	
	7.0	610	0	700	70	2	5	27	0	126
	7.0	610	700	0	700	4	5	8	C	
2.5	6.0	450	0	500	500	1.5	2.5	27	0	127
	6.0	450	500	0	500	1.8	5.5	6	C	
	6.5	550	0	600	600	2	4	28	0	130
	6.5	550	600	0	600	4.5	8	6	C	
	7.0	720	0	800	800	2	5	27	0	130
	7.0	720	800	0	800	5	8	6	C	

The Variac controlling the temperature of the hot wire neutralizer was raised until the floating collector potential was at a minimum. Further increase of the hot wire temperature did not change this minimum.

B. <u>Cesium Plasma Neutralizer</u>

The 60 needle module was tested in a glass enclosed 6 inch pumping system. The module was operated at 7 kv needle voltage, 1" feed pressure, 440 microamps and -600 volts extractor potential.

Operating the module in an all glass system provided an opportunity to visually observe several interesting phenomena. In particular it was possible to observe

1) Electron bombardment of the needles caused the liquid at the needle tip to fluoresce a yellow color.
2) A yellow fluorescence occurred where ions or charged droplets would strike within the chamber
3) Blue fluorescence due to high energy electron impact at the rear of the module was observed
4) A diffuse glow under certain conditions of plasma excitation within the beam was apparent
5) The appearance of discrete jets emanating from needle tips could be seen

The effect of varying extractor bias would easily be seen. High negative bias would cause a generalized yellow glow over the extractor plate.

It is believed this is due to the extractor plate draining ions from the plasma region just in front of the module since the extractor glow is uniformly spread rather than having any tendency to correlate with specific needle locations. The glow also correlated well with the onset of extractor current. Reducing extractor voltage to the order to 300 volts negative or less would first extinguish the extractor glow and then produce a bright yellow glow in all the needles, quickly followed by high intensity arcing. The needle glow was obviously the result of glycerol excitation due to electron bombardment. A low resolution spectrometer indicated that the wavelength may well be that of the sodium D lines arising from the use of NaI dopant. At times when spray jets emerging from the needles and the plasma glow were simultaneously visible it was observed that when the plasma boundary approached too close to the emergent jets complete breakdown would occur. We conclude that quite often an electron-ion plasma exists in front of the module and that this plasma is capable of initiating breakdown whenever a high voltage needle jet approaches its boundary.

While the 60 needle module was in operation an experiment was performed to prove the feasibility of beam neutralization with a cesium plasma neutralizer. Brieflv the neutralizer, Figure 17, consists of a 200°C cesium reservoir feeding a 800°C hollow cathode. A 4 mil exit aperture on the hollow cathode is capable of emitting amperes of electrons along with a small positive cesium ion component to counteract electron space charge. When operating, the neutralizer does not have to be directly in the colloid beam since a highly conducting plasma bridges the gap to the beam. For this part of the run, the module ran at 1.0 ma of beam current.

The experiment was successful in that a floating collector followed the neutralizer potential and the neutralizer current equalled the beam current. Since the neutralizer's low operating temperature minimized its light output it was also possible to visually observe that neutralization had very little effect on beam spread. Unfortunately the cesium supply in the reservoir ran out before more quantitative data could be recorded.

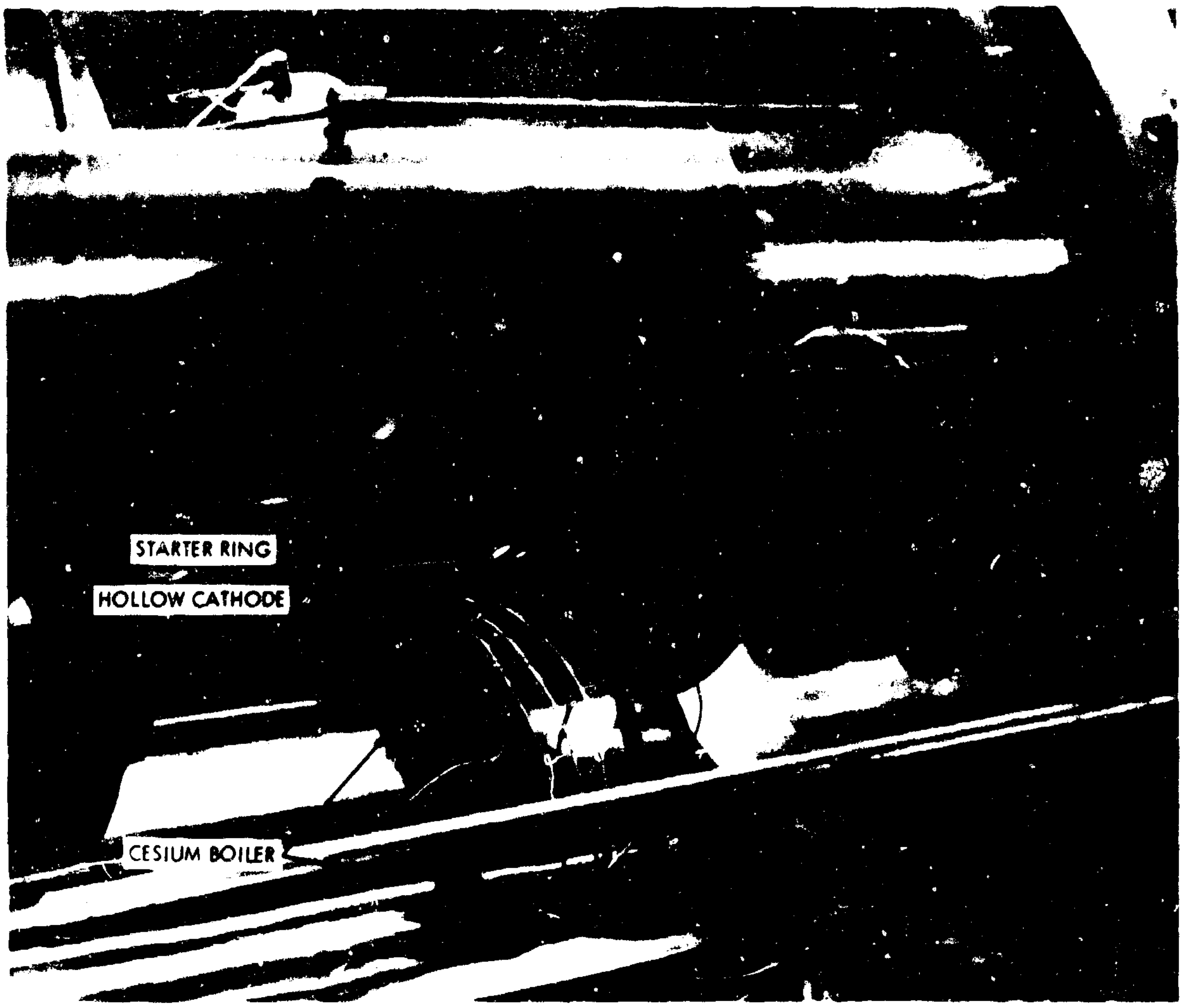


Figure 17. 60 Needle Module With Cesium Plasma Neutralizer.

VII. MATERIALS COMPATIBILITY

An extensive literature search failed to expose any information on corrosion of metals in contact with glycerine doped with sodium iodide or sulphuric acid. Manufacturers and processors of glycerine as well as manufacturers of corrosion resistant metals were contacted to obtain information and suggestions regarding a method of attack on the problem.

The corrosion properties of metals in water solutions of sodium iodide or sulphuric acid has been extensively studied and is well documented over a wide range of Ph, temperature, aeration, etc. Metals which show good resistance to water solutions of NaI and H_2SO_4 were selected for corrosion tests in glycerine under the assumption that glycerine solutions would show some similarity to water solutions.

Since corrosion of metals is essentially an electrochemical process (Ref. 1 Chapter 4) it is natural that various techniques would be devised to measure the changes in the electrical properties of the system. Quantitative corrosion measurements can be made by measuring the change in electrical resistance of a metal in a corroding medium. Since the electrical resistance of a wire, for example, varies inversely with its cross-sectional area the resistance of the wire will increase as its diameter becomes smaller. Therefore a piece of wire exposed in a corrosive solution would show an increase in resistance as it corrodes. The sensitivity of this method is very good and can be as precise as 0.0001 mil.[2 and 3] A corrosion measuring apparatus based upon resistance measurements is marketed under the name "Corrosometer" by the Magna Corp. A masked and an unmasked sample of the metal under test is placed in a corrosive medium and connected to a bridge circuit for resistance measurements. A "Corrosometer" was used to measure the corrosion rates listed in Table 6. The sample to be tested by this method is prepared as shown in Figure 18 by spotwelding current and potential leads plus a center tap to a thin strip of the metal. Half of the sample and the leads are masked by a baked on Teflon coating. The sample was supported by the leads from a connector mounted in the lid of a 1/2 pint mason jar, see Figure 19. The connector was sealed to the jar lid

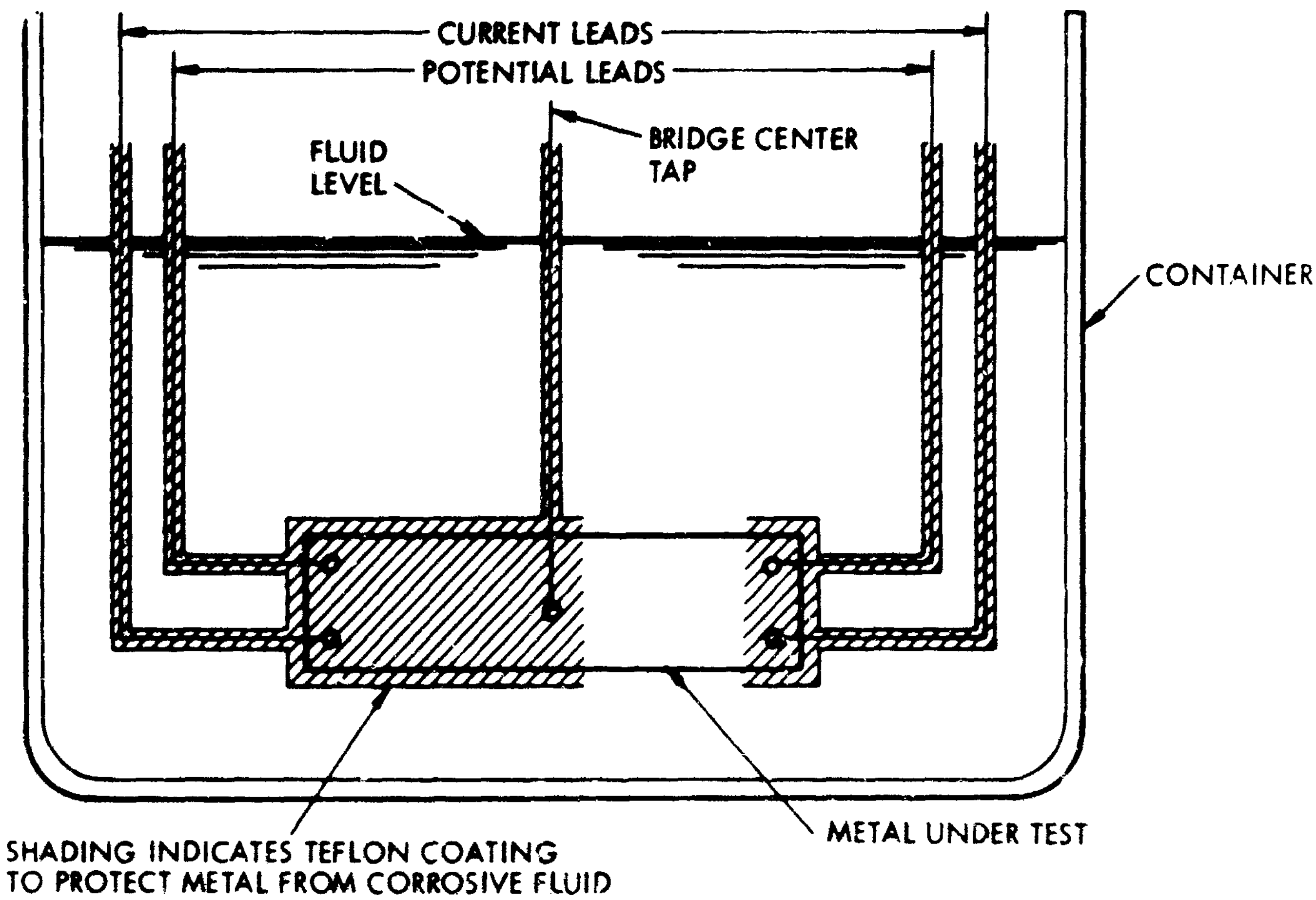


Figure 18. Corrosion Study, Schematic.

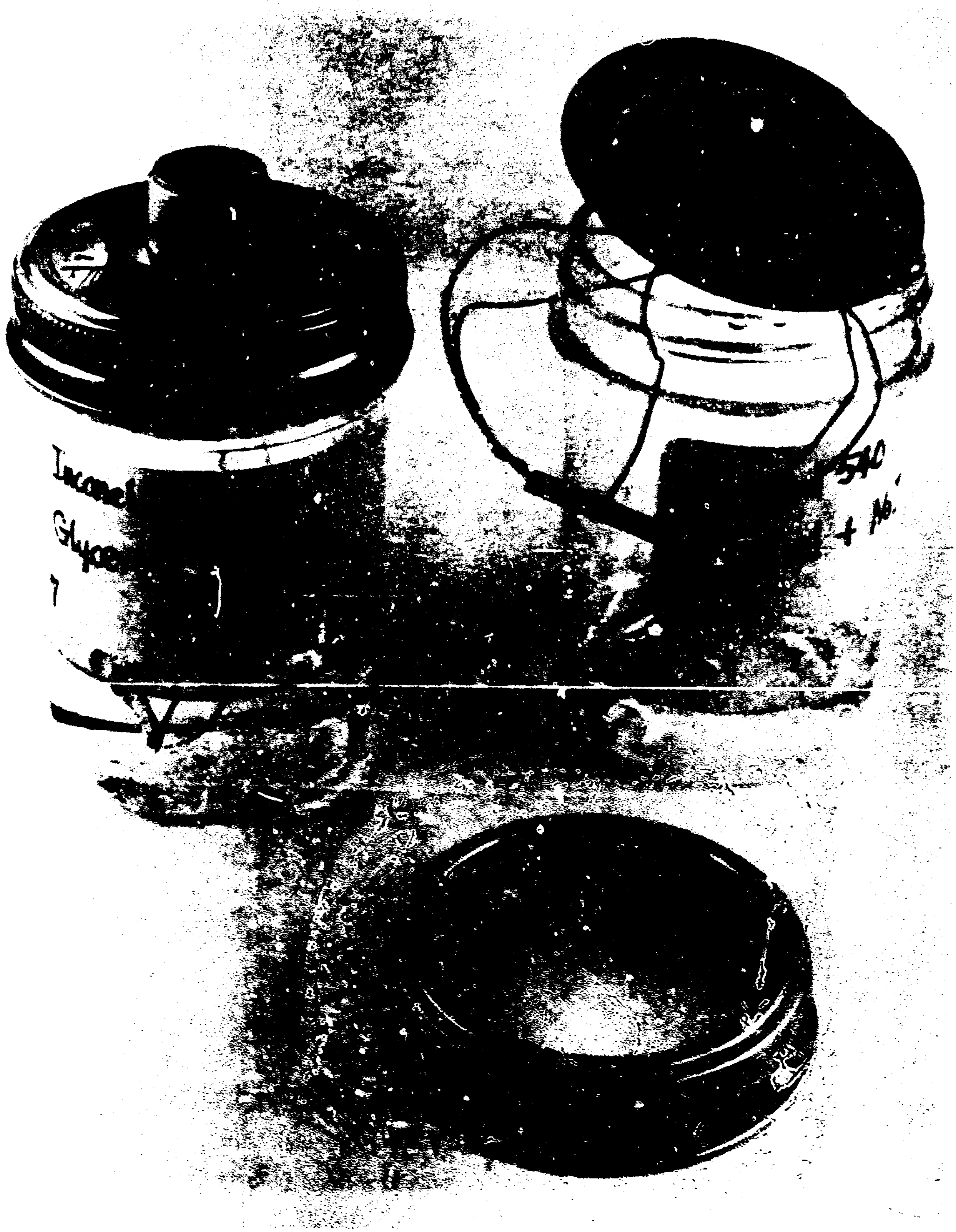


Figure 19. Corrosion Jars.

with Apiezon wax. The doped glycerine was carefully processed to remove water and air. The jar, lid and metal sample, was heated to 150°C and the freshly processed 50°C doped glycerine poured carefully into the jar. The jar was immediately sealed (as in canning food!). By this process it was hoped to eliminate moisture and minimize air inclusion. Corrosion rates at room temperature on 62 days measurements are tabulated in Table 6.

TABLE 6 Materials Corrosion Rates Based on 62 days Measurements

Glycerine Dopant	2% H_2SO_4	20% NaI
MATERIAL (Corrosion rate mils per year)		
Titanium Commercially Pure	Nil	Nil
Ti 6 AL 4V	< 0.1	Nil
6061 T6 AL	0.4	0.1
M400 Monel	Nil	Nil
Inconel 540	.8	(1)
316 SS	(2)	(2)
Ti 0.15 Pd	(2)	(2)
Platinum	(2)	(2)

(1) Defective spot weld on sample

(2) Test Planned

VIII. THRUST MEASUREMENT

A direct measurement of thrust in the millipound region is a simple matter in theory but rather difficult in practice. It is possible to measure the thrustor reaction by mounting it on a platform which may be part of a pendulum device. Another possibility is for the platform assembly to torque a bar and then measure the angular deflection. Both of these general methods are relatively expensive. Because of the low thrusts involved, the feed system and relatively high voltages necessary to operate the colloid thrustor the decision was made to monitor the thrust or more accurately the torque produced by the expellent beam striking a moment arm. This measurement could then be compared with the calculated thrust obtained from experimental data.

(1) $T = \dot{m}v$ but $\dot{m} = \frac{i}{q/m}$, $v = (2V)^{1/2}\ \overline{(q/m)}^{1/2}$

(2) $\therefore\ T = \frac{i}{q/m}\ (2V)^{1/2}\ \overline{(q/m)}^{1/2}$

All the quantities on the right side of this final equation can be obtained from T.O.F. data.

An electromagnetic balance was considered at first. However its fragile nature and beam strength weighed against its use. A torsion balance looked attractive and several of these devices have been fabricated, each time with an improvement.

Figure 1 is a photograph of a preliminary model of a torsion thrust balance along side of the 60 needle module. The metal shield surrounding the thrust balance has been removed. The honeycomb collector has an exposed area of $\approx$ 1 square inch and is placed behind a high transparency fine wire screen grid used for electrostatic shielding. The restoring force torsion wires are each 2 inches long and have a diameter of 0.006 inch. The torsion wires are held under tension and are insulated from the frame. This permits beam current readings to be made from the sampled beam. The left side of the balance beam has an aluminum vane which serves a dual purpose.

It provides damping by virtue of its motion in a magnetic field. It also has index markings which along with a stationary cursor, can be read by means of a telescope situated outside of the vacuum tank. The thrust balance has been found to be remarkably stable. Means are provided for scanning the beam with the torsion balance.

Dynamic calibration of the thrust balance is made as follows:

$$\frac{T_1}{T_2} = \frac{2\pi\sqrt{\frac{I_1}{K}}}{2\pi\sqrt{\frac{I_1 + I_2}{K}}}$$

The period, T_1, of the torsion balance is measured in vacuum without the damping magnet. I_1 is the moment of inertia and K is the torsion constant of the system. Both of these quantities are unknown although the geometry of the wires and mass distributions permit an approximation to be made. If now two equal known masses are placed known distances apart from the supporting wires the incremental moment of inertia I_2 is known. By measuring a new period T_2 a second equation is obtained and the torsion constant K is determined. The thrust balance will be rebuilt several times in order to improve its performance as experience is gained. For this reason no parameters will be given at this time.

IX. COMPUTER PROGRAM, TIME-OF-FLIGHT

A. General

This program is designed to calculate several parameters which describe a beam of charged particles accelerated through a known voltage V. The input quantities are derived from an oscilloscope trace which records beam current at a given distance d from the current source as a function of time elapsed after turning the source off.

The program inputs are in two forms: (a) punched IBM cards in which the oscilloscope trace coordinates have been digitized in a form suitable for computation and (b), a set of input parameters characterizing the experimental conditions for each run. These parameters include quantities such as d, V, conversion factors (k, ℓ) for reducing oscilloscope coordinates to actual times and currents, and a statement of the number of data points appearing on the IBM cards.

B. Specific Requirements

Oscilloscope trace coordinates will be obtained by reading Y coordinates at regularly spaced intervals ΔX, starting at $X = 0$. Thus, after N intervals the coordinates are specified by $(Y, X) = (Y_N, N\Delta X)$. The data will appear on IBM cards as number pairs Y, N where Y is a three digit number and N, which is sequentially numbered from 0 to N_{MAX}, is a two digit number,

Auxiliary data to be supplied with the cards includes:

d = path length (meters)

V = accelerating potential (volts)

k = scale factor to convert Y to microamperes (kY = current)

ℓ = scale factor to convert N to microseconds (ℓN = time)

N_{MAX} = maximum value of N for each run (N always begins at $N = 0$)

The first quantities to be calculated include:

1) $$I_1 = k\ell \, [1/2 \, Y_0 + \sum_{N=1}^{max} Y_N]$$

2) $$I_2 = k\ell^2 \sum_{N=1}^{max} NY_N$$

The final quantities required include:

3) $$\text{Beam efficiency} = \frac{1}{2kY_0} \frac{I_1^2}{I_2}$$

4) $$\text{Mass flow} = \frac{4 \, V \, I_2}{d^2} \times 10^{-18} \text{ kilograms/second}$$

5) $$\text{Thrust} = \frac{.45 \, V \, I_1}{d} \times 10^{-16} \text{ micropounds}$$

6) $$\text{Specific impulse} = \frac{I_1 d}{19.62 \, I_2} \times 10^{6} \text{ seconds}$$

7) $$\text{Average charge to mass ratio } \frac{k \, Y_0 \, d^2}{4 \, V \, I_2} \times 10^{12} \text{ coulombs/kilogram}$$

8) $$\text{SMR charge to mass ratio} = \frac{I_1^2 \, d^2}{8 \, V \, I_2^2} \times 10^{12} \text{ coulombs/kilogram}$$

9) Total current = k Y_0 microamperes

10) The values of I_1 and I_2

11) Two graphs are also required. Graph 1 titled "Mass Distribution" will display

$\frac{dM}{d\,(Q/M)}$ vs Q/M where:

$$\frac{dM}{d\,(Q/M)} = \frac{2 \, k \, \ell^4}{d^4} \; V^2 \, N^5 \; (Y_{N-1} - Y_{N-1} - Y_{N+1}) \times 10^{-30} \text{ (kilogram/second)/(coulombs/kilogram)}$$

$$Q/M = \frac{d^2}{2 \, V \, \ell^2 \, N^2} \times 10^{12} \text{ coulombs/kilogram}$$

Graph 2, title "Current Distribution" will plot $\frac{dI}{d(Q/M)}$ vs (Q/M)

where $\frac{dI}{d(Q/M)} = \frac{k\, \ell^2\, V\, N^3}{d^2} (Y_{N-1} - Y_{N+1}) \times 10^{-18}$ microamperes/ (coulombs/ kilogram)

The final printout should carry a title of the form, "Colloid Time of Flight Data Reduction Run No. 66-4-02-29-2 8 KV 4730 ohm/cm NaI" where the necessary information will be supplied along with the input data for each run.

C. Time-of-Flight Auxiliary Data Sheet

RUN NO: [ ] V = [volts] DOPANT [ohm]

NEEDLE CURRENT [μA]

FEED PRESSURE [ ]

$k = \frac{\mu amps/cm}{div/cm}$ = [ ] μamps/div.

ℓ = μsec/cm x increment (cm) = [ ] μsec/increment

N_{MAX} = [ ] d = [ ] meters

Operators Initials

Date

D. Time-of-Flight Data Analysis

In the past, analysis of T.O.F. data has been accomplished by comparing the actual scope trace to a curve generated with straight lines. The analysis of a number of such straight line geometrical curves has been made and reported upon. Efficiency, average charge/mass ratio, mass flow rate and thrust can be determined easily from the comparison curves. In a few doubtful cases the real T.O.F. trace has been numerically integrated to obtain performance results. This data reduction technique is laborious and time consuming. In order to obtain results faster and more accurately a computer program has been developed which computes all desired beam parameters from a single time of flight trace.

In order to facilitate computer programming of the problems it turned out to be convenient to carry the usual time of flight mathematical analysis one step further than has formerly been done. Usually the beam parameters are derived as functions of the integrals.

$$(1) \qquad I_1 = \int_0^{t_f} t \left(\frac{di}{dt}\right) dt \text{ and } I_2 = \int_0^{t_f} t^2 \left(\frac{di}{dt}\right) dt$$

where t = time elapsed since turning beam off

i = collector current

t_f = time at which collector current has dropped to zero.

These integrals require the inconvenient and relatively inaccurate process of measuring the slope of the time of flight trace at every point. This has now been circumvented by the simple expedient of integrating by parts.

Thus:

(2) $$\int_0^{t_f} t \left(\frac{di}{dt} dt\right) = ti \Big/_0^{t_f} - \int_0^{t_f} i \, dt \text{ or } I_1 = \int_{t_f}^{0} i \, dt$$

(3) $$\int_0^{t_f} t^2 \left(\frac{di}{dt} dt\right) = t^2 i \Big/_0^{t_f} - 2 \int_0^{t_f} i \, t \, dt \text{ or } I_2 = \int_{t_f}^{0} i \, t \, dt$$

Since $i = 0$ when $t = t_f$.

Thus it is no longer necessary to measure the slope of the curve. This refinement has been incorporated into the time of flight data reduction program.

The following equations have been developed utilizing the above relationships:

(4) $$\dot{M} = \frac{4V}{d^2} \int_0^{t_f} i \, t \, dt \quad \text{Mass flow (kg/sec)}$$

(5) $$\eta = \frac{1}{2I} \frac{\left[\int_0^{t_f} i \, dt\right]^2}{\int_0^{t_f} i \, t \, dt} \quad \text{Beam efficiency}$$

(6) $$\overline{(Q/M)} = \frac{I}{\dot{M}} \quad \text{Coulombs/kg}$$

(7) $$\overline{(Q/M)^{1/2}}^{\,2} = \frac{d^2}{8V} \left[\frac{\int_0^{t_f} i \, dt}{\int_0^{t_f} i \, t \, dt}\right]^2 \quad \text{coulombs/kg.}$$

(8) $$T = \frac{2V}{d} \int_0^{t_f} i\,dt$$ Thrust (Newtons)

(9) $$I_{sp} = \frac{d}{2g} \left[\frac{\int_0^{t_f} i\,dt}{\int_0^{t_f} i\,t\,dt} \right]$$ Specific Impulse (Seconds)

(10) $$\frac{d\dot{M}}{d(Q/M)} = \frac{-2V^2 \quad t^5}{d^4} \frac{di}{dt}$$ Mass Distribution Function

(11) $$\frac{dI}{d(Q/M)} = \frac{-V\,t^3}{d^2} \frac{di}{dt}$$ Current Distribution Function

where V = accelerating voltage

d = time of flight distance (meters)

I = steady state collector current

$g = 9.8\ m/sec^2$

The first step in the time of flight data analysis is to record time of flight oscilloscope trace coordinates in digital form. This is done with a Telecordex scanning machine which automatically enters the data on IBM cards as the devices cross hairs are scanned over a projected trace image. The computer program then utilizes the IBM cards as input data to generate the required set of parameters.

X. THRUSTOR DESIGN

Essentially the first half of this two year program has been spent in acquiring performance characteristics of both individual capillary needles and ensembles of needles. It is apparent that beam currents of 300 microamperes and greater are available from a 37 needle module. Average specific charge ratios have been obtained ranging from 2500 to 6000 coulombs/kilogram. In order to maintain a specific impulse of 2000 seconds and a thrust of two millipounds, the following performance choices are at our disposal.

Q/M	$I_{\mu a}$	V_{KV}
2000	900	100
4000	1800	50
6000	2700	33.3

A conservative and prudent decision would be to design the thrustor in such a fashion as to insure a 3000 microampere beam. This decision is acceptable and a mechanical design study is now underway. Eight modules, each containing 37 needles, will be positioned in a linear-array. In the gravity field mandated by the necessity to test an engine in an earth bound laboratory, a circular array of eight modules positioned in a vertical plane would cause a serious pressure feed differential between the uppermost and the lowest needles. The choice of operating specific charge and therefore post acceleration will be determined principally by the ability of the test vacuum chamber to maintain adequate pressure (5×10^{-6} torr) in view of the mass flow rate of expellant. Figure 20 is an artist's view of the thrustor system.

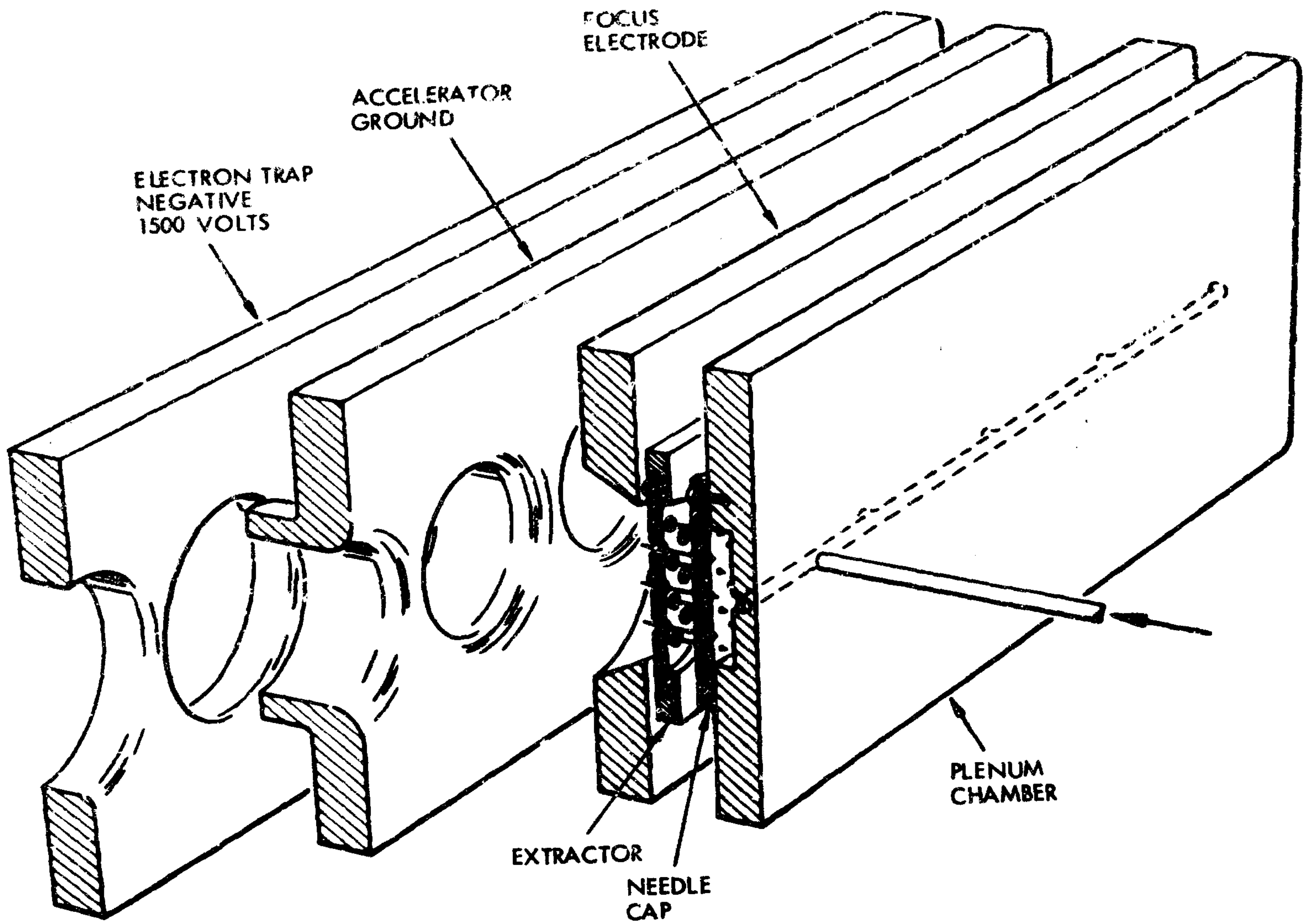


Figure 20. Two Millipound Thruster Schematic.

XI. CONCLUSIONS

Although significant progress has been made toward obtaining the immediate goals of the present contract much work remains to be done. Certainly the advantages of the colloid thrustor have been borne out particularly in the micropound region of operation. This fall-out in the quest of a millipound engine for stationkeeping applications is an exciting one. Throttleable thrust ranges extending from 1 to 100 micropounds at an I_{sp} of 500 to 800 seconds with efficiencies greater than 75% are now considered normal operation at TRW Systems. Although the thrustor is only one part of the flight hardware demanded for space application, it is a significant part. The generation of the flight hardware is considered a task utilizing merely state-of-the-art hardware for the most part. In addition the demands of flight qualified colloid thrustor points up new information that must be determined to insure the success of a colloid system of propulsion.

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