M-4 July 2, 1964

Mr. R. G. Sweet
Applied Electronics Laboratory
Stanford University
Stanford, California

Dear Mr. Sweet:

I find your direct-writing oscilloscope to be a clever and fascinating device and would greatly appreciate receiving whatever detailed information you can provide. Is production of this instrument planned? If so, when and by whom? I thank you in advance.

Sincerely yours,

Mack J. Fulwyler

MJF:ES

Correspondence and notes contributed by Bob Auer

STANFORD ELECTRONICS LABORATORIES

STANFORD, CALIFORNIA

July 7, 1964

Mr. Mack J. Fulwyler
Los Alamos Scientific Laboratory
P.O. Box 1663
Los Alamos, New Mexico

Dear Mr. Fulwyler,

I am enclosing a copy of our final report in response to your inquiry of July 2 about our oscillograph. Honeywell Inc. has been granted a license for commercial rights, and their Denver Division is presently evaluating the feasability of commercial development of the system.

Thank you for your interest in our project.

Very truly yours,

Richard Sweet
Research Associate
Systems Techniques Lab

Encl: TR 1722-1
RS/kp

14 July '64
Called Mr. Sweet, he said that
11 - 12 August should be fine for
a visit. Must write confirming ltr.

M-4 July 16, 1964

Mr. Richard Sweet
Systems Techniques Laboratory
Stanford Electronics Laboratory
Stanford, California

Dear Mr. Sweet:

As we discussed during our telephone conversation of July 14, I would like to visit with you on August 12 and/or 13 to discuss a possible application for your writing oscillograph. If these dates are satisfactory, please notify me at the following address: Mack J. Fulwyler, c/o Howard W. Tucker, 274 Sorenson, Pocatello, Idaho. Thank you.

Sincerely yours,

Mack J. Fulwyler

MJF:ES

16 July

Question on Feasibility of Cell Separation

1.) Might it be better to vary the deflection plate voltage holding charge constant? This might lessen pickup by Coulter aperture system.

2.) Would RBC presence perturb formation of droplet? (I think not as the ratio of RBC vol/drop vol ~ 2000.) No prob.

3) Electrical sick-up of the deflection voltage pulse by the aperture system. (May be a problem)

4) How much flexibility exist in the following parameters:

a. Drop frequency 250kc → 10kc

b. Drop size

c. Driving pressure → 11 psi and up to 60 psi

d. Nozzle-paper separation distance

5) What results from variations in fet length ? Directly proportional to pressure

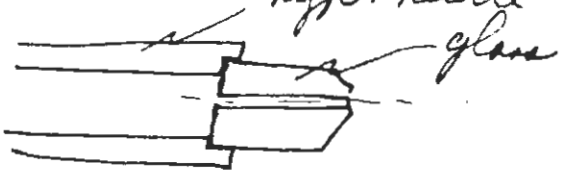
Page 32 6) Although I don't understand why, air flow appears to increase diffiation obtained with a given input

7) How about a two nozzle (dual chan) system?

Page 46 8. What is your most recently developed nozzle and mount schme

Page 48 9.) He says, Both accuracy may be obtained in a system having with a lower drop - rep rate or lower max. trace deflection.

Page 62 10. Nozzle Construction used



11. I would like to operate at low fluid pressure ~ 5 p.s.i.

11. I don't think one can ~~vary~~ vary the deflection plate voltage rather than ~~the~~ the changing voltage

12. The jet formed is 35 μ in diameter. The jet velocity is ~ 22 m/sec

Droplets formed by this jet have a diameter of ~ 75 μ & a vol. = $2.3 \times 10^5\ \mu^3$.

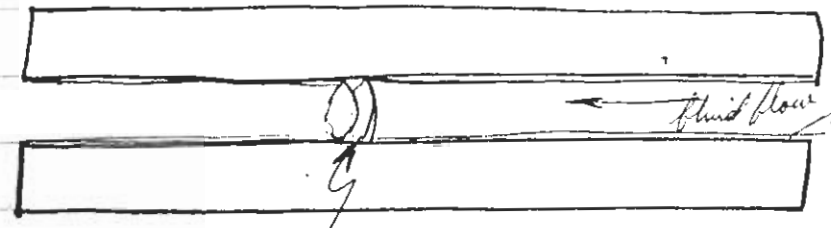
If we use an aperture of ~ 2000 μ in length 35 μ in diameter the cell transit time will be

$$\frac{2 \times 10^{-1}\ cm}{2.2 \times 10^{3}\ cm/sec} \simeq 1 \times 10^{-4}\ sec = 100\ \mu sec$$

Volume rate of flow = $\pi r^2 v = \frac{\pi (35)^2}{4} \times 2.2 \times 10^7\ \mu/sec$

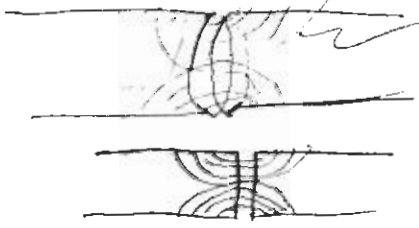
$= 2.1 \times 10^{10}\ \mu^3/sec = 2.1 \times 10^{-2}\ cm^3/sec$

13. A possible idea for incorporating an aperture in to a tube



coat inside of tube with Nickle by decomposition of $Ni(CO_2)_2$

aperture



probable line of force.

Correspondence and notes contributed by Bob Auer

STANFORD ELECTRONICS LABORATORIES

STANFORD, CALIFORNIA

521-2300

July 20, 1964

Mr. Mack J. Fulwyler
c/o Howard W. Tucker
274 Sorenson
Pocatello, Idaho

Dear Mr. Fulwyler,

I am looking forward to seeing you on August 12 or 13 and can easily arrange to have at least part of either day available. Please let me know when you plan to come as soon as your plans are definite.

There are two items that perhaps require clarification. First, although all the essential parts of our experimental systems are available, the equipment was dismembered some time ago, and I cannot show you an operating system. Second, Honeywell Inc. holds an exclusive license to commercial patent rights for the technique, and this would probably have to be considered in applications to non-government uses.

Very truly yours,

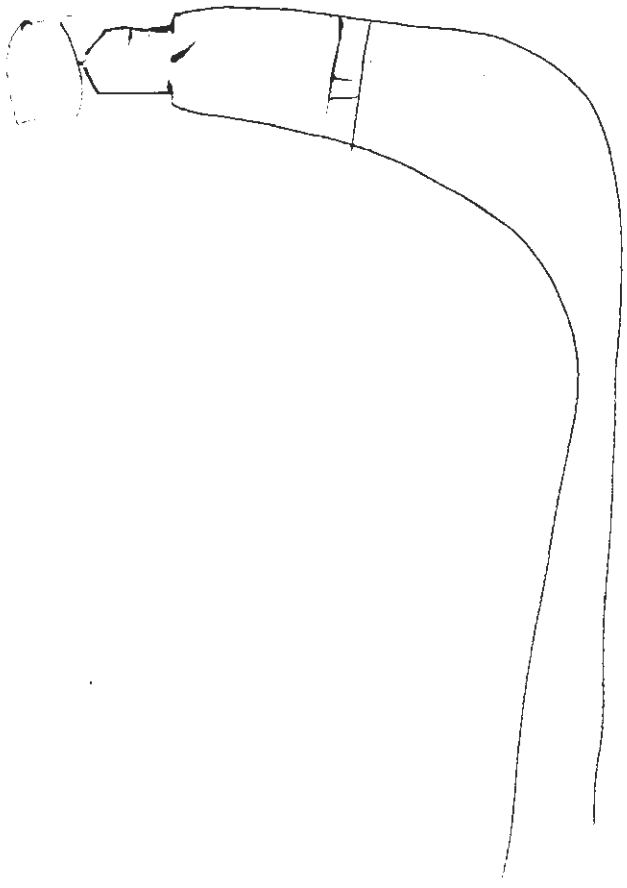
Richard Sweet

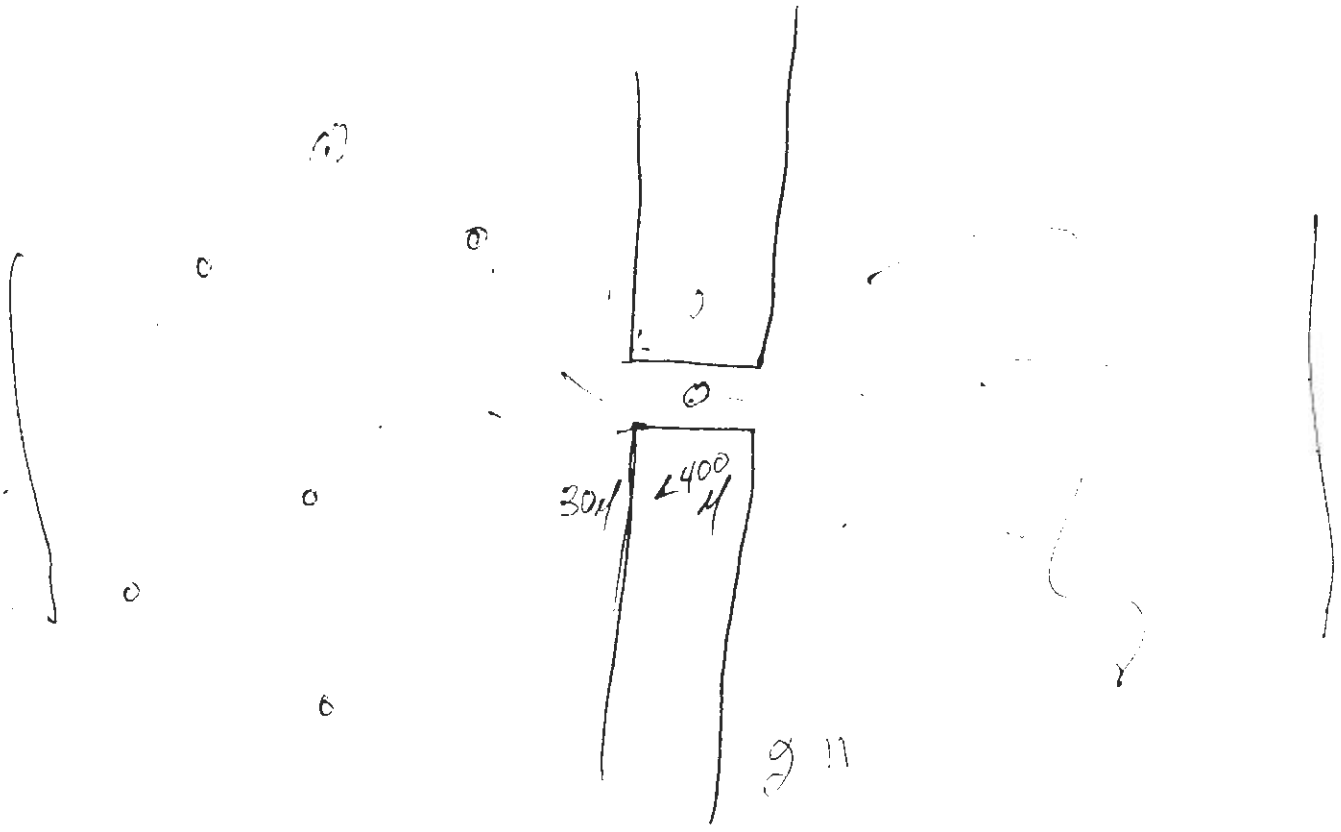
Richard Sweet
Research Associate
Systems Techniques Lab

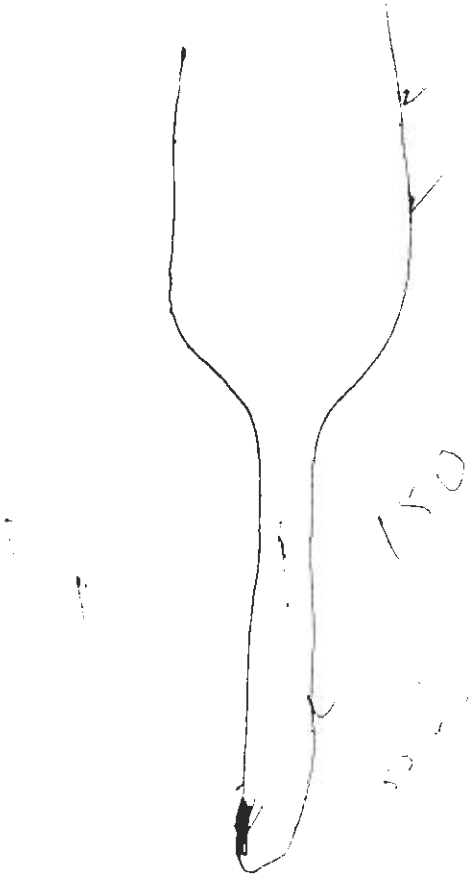
RS/kp

DA 13300
Ext. 466
2 P.M. Up Un. Ave.
bear North of campus.
applied electronics Laboratory
next to electronic research
lab.

Correspondence and notes contributed by Bob Auer




30'
400'



1. Has used

11 psi, nozzle diam - .0011 inch
jet diam. .00125"
drop spacing - .0091 inch
drop freq. — 31 kc
jet vel. — 282 inch/sec
deflect. voltage across plate 7KV/.375" inch

2. Thinks that a grounded metal section between aperture and nozzle might avoid electrical feedback to ~~the~~ aperture system

3. Krohn-Hite DRA-10 appl. to drive vibrator (nozzle

Your letter of August 18 indicates that this may have gone astray — here is another copy — G. Sweet

Correspondence and notes contributed by Bob Auer

August 14, 1964

Mr. Mack J. Fulwyler
Low Alamos Scientific Laboratory
P.O. Box 1663
Los Alamos, New Mexico 87544

Dear Mr. Fulwyler,

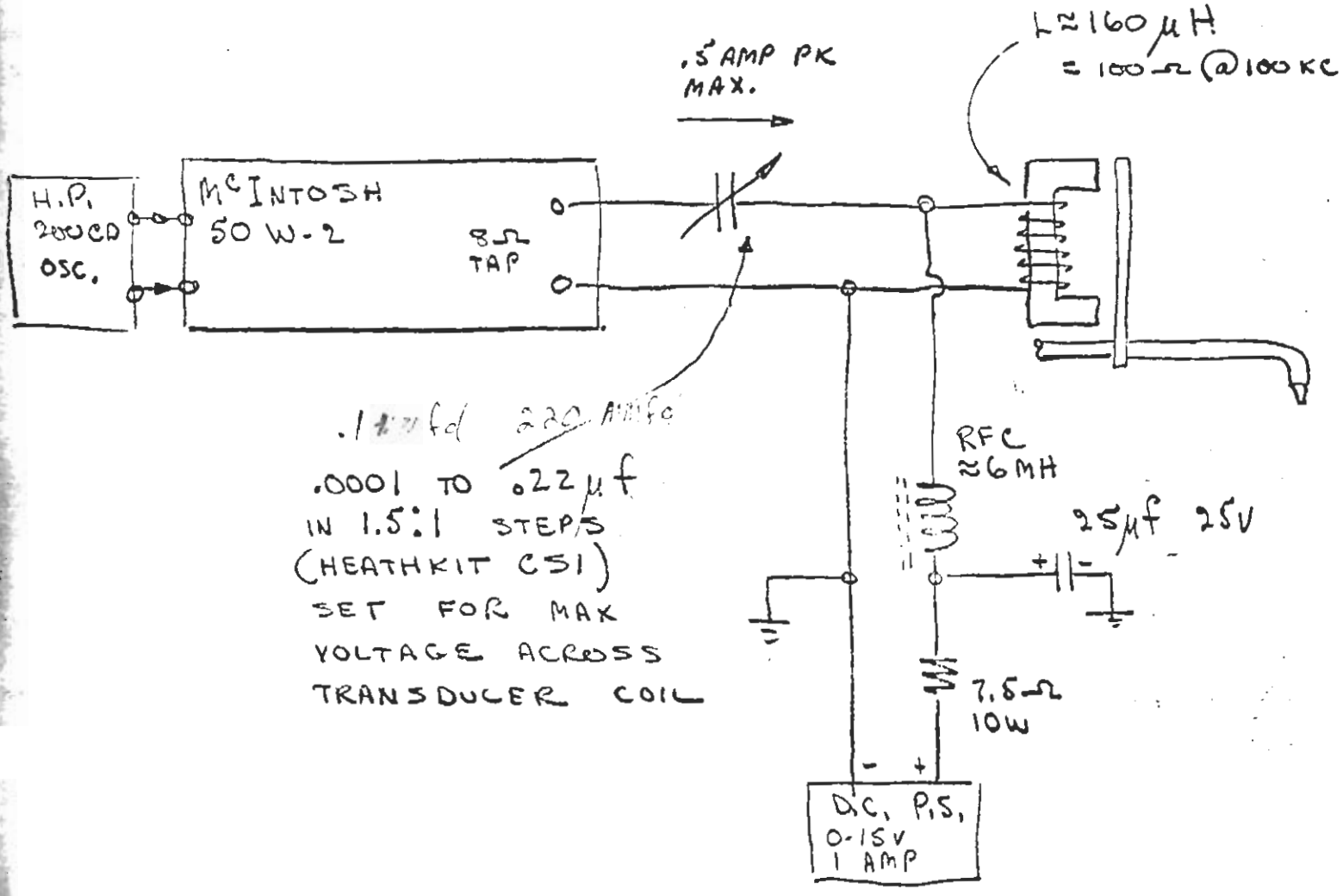
I want to thank you for a most interesting and stimulating discussion during your visit yesterday. After giving your ingenious cell-sorting scheme additional thought, my only conclusion is that it will surely work. I certainly hope that you are successful in developing this and am looking forward to hearing more about it.

The amplifier and transducer driving schematics are enclosed. If there is any other information that I have that would be of use to you, please let me know.

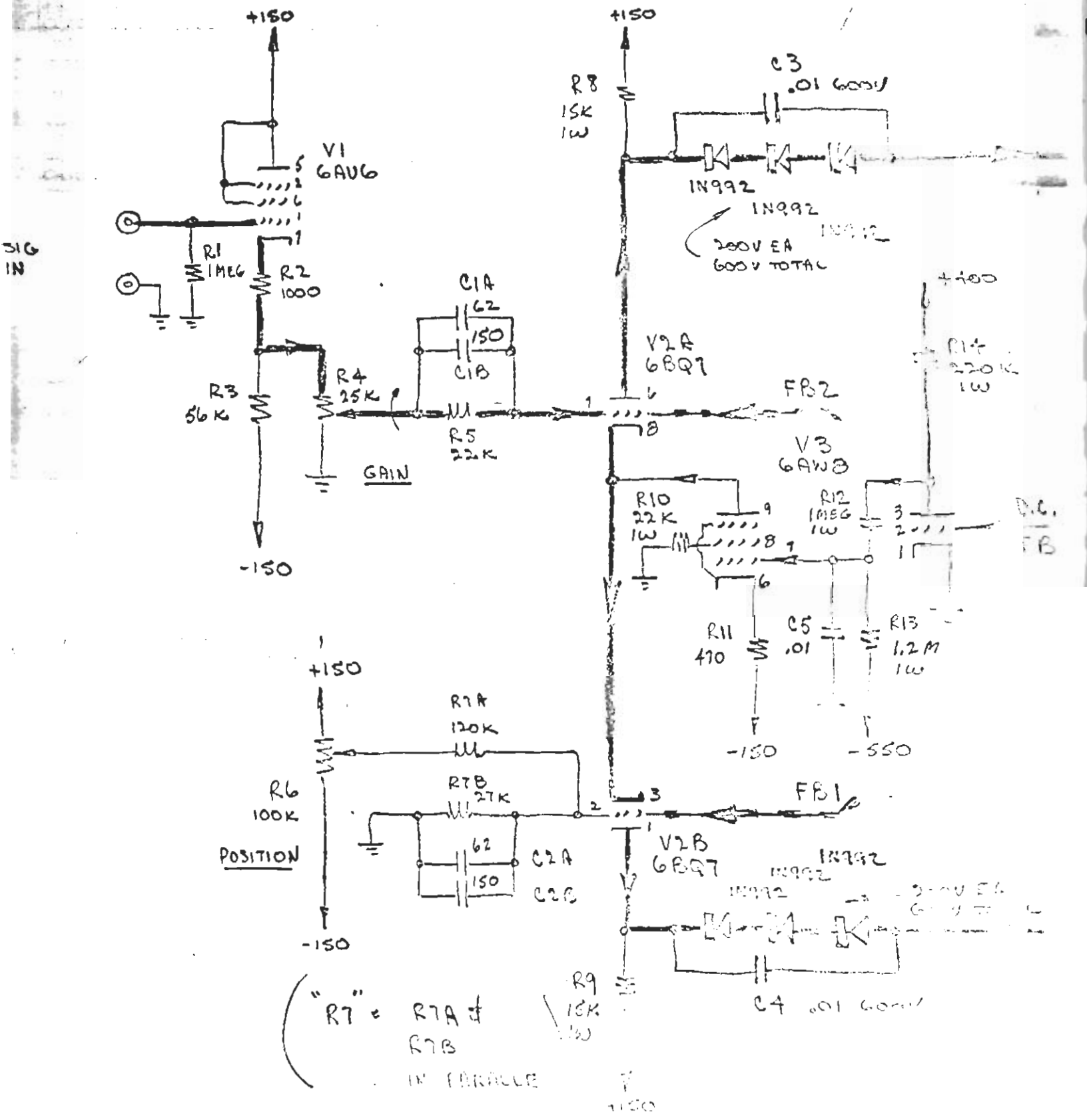
Best Regards,

Richard Sweet
Research Associate
Systems Techniques Lab

RS/kp
Encls.

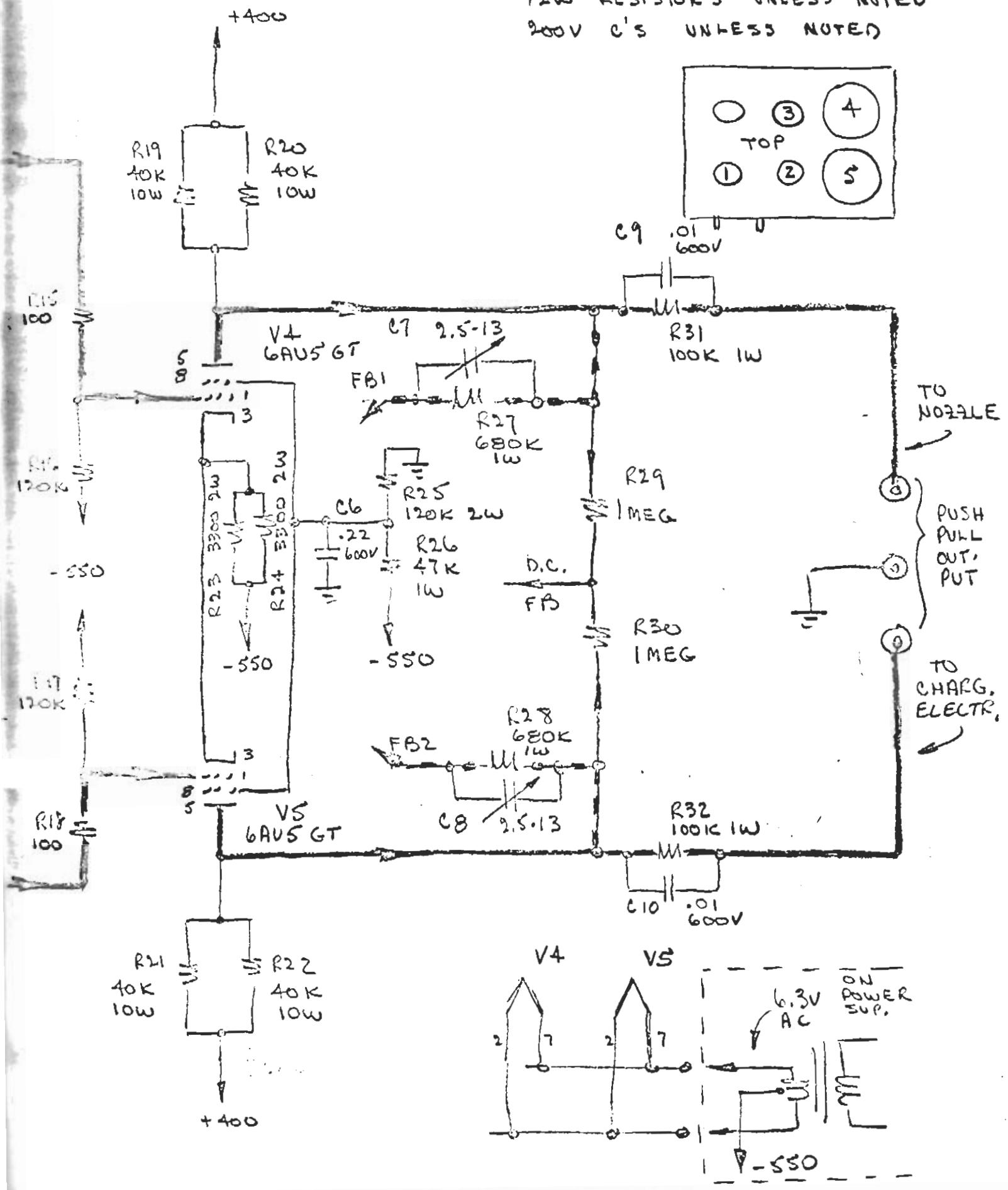


MAGNETOSTRICTIVE TRANSDUCER BIASING & TUNING CIRCUITS


+150
V1
6AU6
SIG IN
R1 1MEG
R2 1000
R3 56K
R4 25K
GAIN
-150
C1A .62 150
C1B
R5 22K
V2A 6BQ7
R8 15K 1W
C3 .01 600V
IN992
IN992
200V EA 600V TOTAL
FB2
+100
R14 220K 1W
V3 6AW8
R10 22K 1W
R12 1MEG 1W
D.C. FB
R11 470
C5 .01
R13 1.2M 1W
-150
-550
+150
R7A 120K
R7B 27K
R6 100K
POSITION
-150
C2A .62 150
C2B
FB1
V2B 6BQ7
IN992
IN992
R9 15K 1W
C4 .01 600V
"R7" = R7A # R7B IN PARALLEL
+150

D.C. COUPLED PUSH-PULL AMPLIFIER

1/2W RESISTORS UNLESS NOTED
200V C'S UNLESS NOTED



STANFORD ELECTRONICS LABORATORIES

STANFORD, CALIFORNIA

August 14, 1964

Mr. Mack J. Fulwyler
Los Alamos Scientific Laboratory
P.O. Box 1663
Los Alamos, New Mexico 87544

Dear Mr. Fulwyler,

I want to thank you for a most interesting and stimulating discussion during your visit yesterday. After giving your ingenious cell-sorting scheme additional thought, my only conclusion is that it will surely work. I certainly hope that you are successful in developing this and am looking forward to hearing more about it.

The amplifier and transducer driving schematics are enclosed. If there is any other information that I have that would be of use to you, please let me know.

Best Regards,

Richard Sweet

Richard Sweet
Research Associate
Systems Techniques Lab

RS/kp
Encls.

M-4 August 18, 1964

Mr. Richard Sweet
Systems Techniques Laboratory
Stanford Electronics Laboratories
Stanford University
Stanford, California

Dear Mr. Sweet:

The loan of the ink-drop gun is a great help and is certainly appreciated.

As we discussed, I am looking forward to receiving diagrams of the driver for the nozzle vibration system and of the droplet charging system.

Again, thanks for your time and cooperation. My visit was very profitable, and I greatly enjoyed my first trip to the San Francisco area.

Sincerely yours,

Mack J. Fulwyler

MJF:ES

M-4 August 20, 1964

Mr. Richard Sweet
Systems Techniques Laboratory
Stanford Electronics Laboratories
Stanford University
Stanford, California

Dear Mr. Sweet:

Thank you for the schematics and for your encouraging comments. I appreciate your assistance and will keep you informed.

Sincerely yours,

Mack J. Fulwyler

MJF:ES

H-4 April 21, 1965

Mr. Richard Sweet
Systems Techniques Laboratory
Stanford Electronics Laboratories
Stanford University
Stanford, California

Dear Mr. Sweet:

After a long silence I thought it time to tell you of the progress I have made on the cell separator mentioned during our discussion of August 1964.

Although a number of problems were encountered, they have been overcome and in the past two weeks I have been able to separate several different kinds of biological cells and non-biological particles. The device is still crude, but I hope to have a brief description in print soon.

I am now ready to return the ink-drop gun you loaned me; however, I chipped the end of the nozzle in trying to unplug a lodged particle. I ground the nozzle back past the broken portion, as you can see in the enclosed photographs. The diameter of the emerging stream is now 50 microns. If this is still useful to you, I can return the gun as is; however, if you wish, I will gladly replace it with a smaller nozzle.

Please let me say again that I appreciate your interest and assistance in this project. The device is creating a lot of excitement and should find many important applications in biological and medical research.

Sincerely yours,

Mack J. Fulwyler

MJF:ES
Enc. 2 photographs

Correspondence and notes contributed by Bob Auer

STANFORD ELECTRONICS LABORATORIES

STANFORD, CALIFORNIA

April 26, 1965

Mr. M. J. Fulwyler
University of California
Los Alamos Scientific Laboratory
P.O. Box 1663
Los Alamos, New Mexico 87544

Dear Mr. Fulwyler:

I was pleased to receive your letter of April 21 and to learn of your progress with the cell separator. Please don't be concerned about the enlargement of the nozzle in the ink drop gun--just send it back "as is". I am glad that it was of use to you.

The photo enclosed with your note is quite impressive. I wonder if you have attempted to take similar pictures of the drop formation process, using strobe illumination, and if so, how they turned out.

I am looking forward to seeing a published description of your work. I am naturally curious to learn more about its details, and hope that you will eventually be able to send me some kind of report on your ingenious system.

Very truly yours,

Richard G. Sweet

R. G. Sweet
Research Associate

RGS:km

H-4 May 21, 1965

Mr. Richard Sweet
Stanford Electronics Laboratories
Stanford University
Stanford, California

Dear Mr. Sweet:

I am returning your ink drop gun under separate cover. I hope you receive it in good shape.

Enclosed are several pictures of the drop formation process, which you may keep. If you are interested in the operating conditions under which they were taken, please let me know. The cell separator should appear in print soon; right now it is held up by patent processing. I will send you a reprint when available.

Again, thank you for your help and interest.

Sincerely yours,

Mack J. Fulwyler

MJF:ES
Enc. 6 prints

Sep. Cover - 1 ink drop gun

CC:W. J. Weber - H-DO
H. Dubberly - SP-1

H-4 May 21, 1965

Mr. Richard Sweet
Stanford Electronics Laboratories
Stanford University
Stanford, California

Dear Mr. Sweet:

I am returning your ink drop gun under separate cover. I hope you receive it in good shape.

****

Sincerely yours,

Mack J. Fulwyler

MJF:ES

Sep. Cover - 1 ink drop gun

CC:W. J. Weber - H-DO
H. Dubberly - SP-1

M-4 January 24, 1966

Mr. R. A. Sweet
Stanford Electronics Laboratories
Stanford University
Stanford, California

Dear Mr. Sweet:

I am enclosing a reprint of the separator article which appeared in the November 12, 1965, issue of Science. If you are interested, I will be glad to give you more information on the device.

Dr. Leonard Herzenberg of the Genetics Department at the Stanford Medical School is considering building a separator for research involving the biology of cells.

Did you receive your ink drop gun in good condition? What about the droplet pictures?

Sincerely yours,

Mack J. Fulwyler

MJF:ES
Enc. 1 reprint

Correspondence and notes contributed by Bob Auer

STANFORD ELECTRONICS LABORATORIES

STANFORD, CALIFORNIA

February 1, 1966

Mr. Mack J. Fulwyler
Los Alamos Scientific Laboratory
P.O. Box 1663
Los Alamos, New Mexico 87544

Ref: H-4

Dear Mr. Fulwyler:

Thank you for your letter of January 24, and the enclosed reprint. I think your project is most interesting and wish to congratulate you on your beautiful work.

I would very much appreciate any additional detailed information that you could supply me, particularly concerning details of your drop forming and launching system and Coulter aperture. Also useful would be information on your experience in methods of avoiding satellite drops and in minimizing and stabilizing the length of the unbroken jet extending to the drop separation point.

I would assume from the June submission date that the published article is now quite obsolete and that you are currently realizing even better performance. I hope you can tell me something of your present efforts and expectations.

I received my ink drop gun in perfect condition, and the photos enclosed with your letter. I am enclosing Xerox copies of your own photos and I would be grateful if you could note on these the drop repetition frequency and a scale reference, such as the drop-to-drop spacing, and return them to me.

I hope that I will sometime have an opportunity to meet you again and to discuss our experience in more detail. If you should be in the bay area I would be most pleased to see you and hope that you could plan to spend some time at Stanford.

Cordially,

Richard Sweet
Research Associate

RS:km

encls.

Reply-25 Feb

Reprinted from THE REVIEW OF SCIENTIFIC INSTRUMENTS, Vol. 36, No. 2, 131-136, February 1965
Printed in U. S. A.

High Frequency Recording with Electrostatically Deflected Ink Jets*

RICHARD G. SWEET
Systems Techniques Laboratory, Stanford Electronics Laboratories, Stanford University, Stanford, California
(Received 28 September 1964)

A high speed oscillograph, using ordinary ink and paper, has been developed that provides a new approach to the old problem of producing instantly visible, high frequency records with inexpensive writing materials. A high speed jet of ordinary fountain-pen ink is divided into a uniform procession of drops, each of which is independently charged in proportion to an input-signal voltage. After projection through a constant transverse-deflecting field, the charged drops are collected on a moving chart to form an instantly visible, permanent record of the input signal. Drops are typically formed at a rate of 100 000/sec; each has an independent trajectory and makes an individual mark representing an independent sample of the input waveform. The ink stream may be switched on or off at high speed by providing, between the drop-launching point and the record surface, a collector that intercepts drops having a specific trajectory. Besides oscillography, which is discussed in detail, the technique has applications in other fields requiring marking at high speed or marking without pressure or physical contact.

INTRODUCTION

CURRENTLY used pen or stylus oscillographs are limited to input signals having frequency components below a few hundred cps, while recorders useful in the kilocycle range generally capture the signal information on a relatively expensive and inconvenient light-sensitive medium. This paper describes a high speed oscillograph, using ordinary ink and paper, that provides a new approach to this old problem of producing instantly visible, high frequency records with inexpensive writing materials.

The system writes with a jet of ink that is electrostatically charged and deflected in accordance with the input signal potential. The technique differs from methods used in previous jet-writing systems in that the ink stream is divided into a regular procession of uniform drops, and the drop charge, rather than the deflecting field, is controlled by the input signal. Each ink drop leaves on the record surface a mark that represents an independent sample of the input-signal amplitude, taken at the instant the drop was charged. In a typical oscillograph, drops are charged and launched at a repetition frequency of 100 000/sec, and although about 200 drops are simultaneously in flight, each has an independent trajectory. The high frequency detail that can be recorded is determined only by the rate at which drops are formed, and not by the transit time required for them to traverse the constant-deflection field.

BACKGROUND

The recording system writes with fluid drops having precise uniformity in size, repetition frequency, and initial velocity. The drops are generated by the division of a regularly disturbed cylindrical jet, a process first described in 1833 by Felix Savart,[1] and later treated analytically by Raleigh,[2] Weber,[3] and Goren.[4] As they form, the drops are charged by electrostatic induction, using essentially the same configuration employed by Kelvin[5] in 1867 for charging the water drops in his electrostatic generator. Magnus[6] showed in 1859 that the drops in a regular procession of uniform fluid drops, formed in a constant electric field, follow identical curved trajectories, and this principle has been employed by Waage[7] in a cathode-ray-tube demonstration model that uses water drops to represent electrons. Recently, Magarvey and Blackford,[8] Mason and Brown-

* Prepared under Signal Corps Contracts DA 36(039) SC-87300 and DA 36(039) AMC-03761(E).

[1] Felix Savart, Ann. Chim. Phys. **53**, 337 (1833).
[2] Lord Rayleigh, Proc. Roy. Soc. (London) **29**, 71 (1879).
[3] C. Weber, Z. Angew. Math. Mech. **11**, 136 (1931).
[4] S. L. Goren, J. Colloid Sci. **19**, 81 (1964).
[5] Lord Kelvin, Proc. Roy. Soc. (London) **16**, 67 (1867).
[6] G. Magnus, Phil. Mag. **S4. 18**, 161 (1859).
[7] H. Waage, Am. J. Phys. **24**, 478 (1956).
[8] R. H. Magarvey and B. L. Blackford, J. Geophys. Res. **67**, 1421 (1962)

Correspondence and notes contributed by Bob Auer

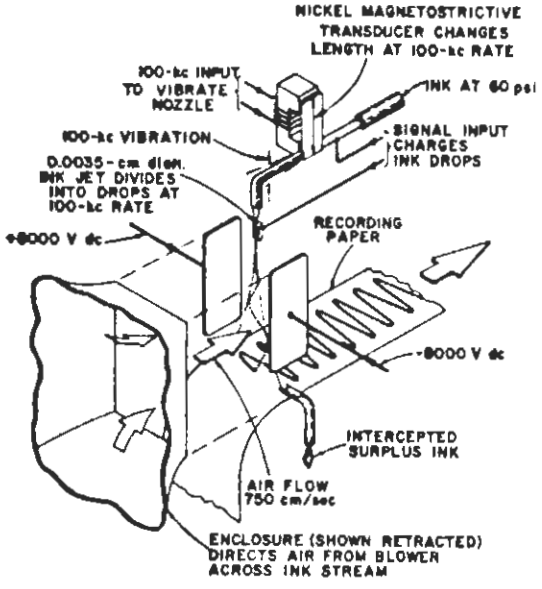


FIG. 1. Ink-jet oscillograph.

scombe,[9] and Schneider[10] have reported on techniques for forming, charging, and deflecting water drops, using methods similar to those described here.

Writing techniques employing fine jets of ink have a history extending back to at least 1873. One version of Kelvin's[11] "siphon recorder," and the Elmqvist[12,13] system now used in commercial oscillographs in Europe, use an ink jet issuing from a nozzle that is aimed by the moving coil of a galvanometer. Jet writers patented by Hansell,[14] Schroter,[15] Richards,[16] and Winston[17] deflect ink jets with electrostatic or magnetic fields; however, the transient-response time of these systems is limited by the time required for the ink to traverse the deflection field.

SYSTEM CONFIGURATION

Figure 1 shows the configuration of an experimental oscillograph and gives an example of typical parameter values. Ordinary fountain-pen ink (Schaeffer's "Scrip"), having fluid properties similar to those of water, is supplied at a pressure of 4.2 kg/cm^2 to a nozzle having an exit diameter of 0.0035 cm. The resulting cylindrical jet of ink emerges with an initial velocity of 2100 cm/sec and a volume flow rate of 0.02 cc/sec. Most of the 3.5-cm flight from nozzle to paper takes place in a constant transverse electric field of 16 kV/cm.

[9] B. J. Mason and J. L. Brownscombe, J. Sci. Instr. 41, 258 (1964).
[10] J. M. Schneider, Rept. CPRL-2-64, Charged Particle Res. Lab., University of Illinois, Urbana, Illinois (1964).
[11] Lord Kelvin, Trans. Inst. Engr. Shipbuilders Scotland (18 March 1873).
[12] R. Elmqvist, U. S. Patent 2,566,443 (1951).
[13] W. Kaiser, Siemens-Rev. 26, 191 (1959).
[14] C. W. Hansell, U. S. Patent 1,141,001 (1933).
[15] F. Schroter, U. S. Patent 1,882,043 (1932).
[16] C. H. Richards, U. S. Patent 2,600,129 (1952).
[17] C. R. Winston, U. S. Patent 3,060,429 (1962).

Figure 2 is an exploded view showing the principal components of the assembly that launches and charges the ink. The tiny glass nozzle, cemented into the end of the metal supply tube, points to the left. The ferrite core and coil magnetize the strip of nickel brazed to the nozzle supply tube at a frequency of 100 kc, and magnetostriction of the nickel results in vibration of the nozzle along its axis at the excitation frequency. The ink-drop-charging electrode, just to the left of the nozzle, has a U-shaped cross section where it surrounds the jet. The jet passes between the sides of the U, spaced 0.050 cm apart, entering as a continuous stream and emerging as a series of discrete drops. The electrode is pivoted so that it can be swung away from the jet to facilitate observation of the drop-formation process.

DROP FORMATION

Surface tension acts to decompose the unstable cylindrical jet issuing from the nozzle into drops having a smaller total surface area and lower surface energy. The nozzle vibration modulates the velocity of the ink jet and establishes an axially symmetric disturbance in the jet profile that initiates the breakup process. Once established, the disturbance envelope grows exponentially, finally severing the jet at regularly spaced intervals. Drops form in exact synchronism with the 100-kc nozzle vibration—the distance from the nozzle at which the drops separate, and their size and spacing, are determined, within limits, by the vibration amplitude and frequency. Surface-tension forces are opposed mostly by fluid inertia in the breakup process. Jet surface charge induced by the signal input causes electrostatic forces that oppose surface tension; the effect on disturbance growth is small for the maximum input potentials used. Viscous forces are negligible[3] if the square of the ink viscosity is small compared with the product of ink density, ink surface tension, and jet diameter—this is the case for the ink actually used.

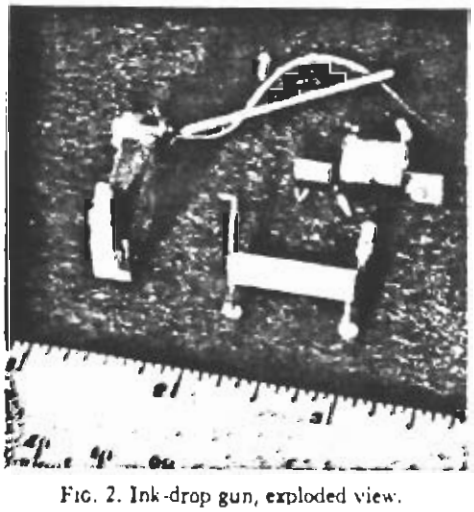


FIG. 2. Ink-drop gun, exploded view.

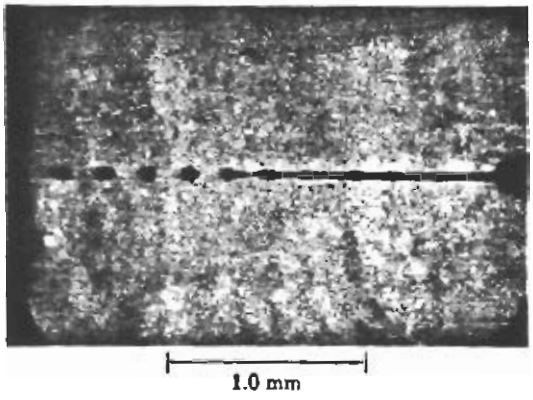


FIG. 3. Ink-drop formation.

The instant of drop separation is defined by the breaking of the fine fluid ligament connecting a drop in the final stage of formation to the parent jet. Under some conditions, the ligament breaks at more than one point, forming a tiny secondary or satellite drop ("Plateau's spherule"). The tendency for this secondary drop formation is increased when the jet is charged. Surface charge also enhances a tendency for the main drops to subdivide if the sections into which the jet is resolved are too long.

To minimize electrostatic and aerodynamic interaction between neighboring drops in flight, the initial drop-to-drop spacing, equal to the disturbance wavelength on the undivided jet, should be as large as possible. Subdivision of the main drops limits the ratio of disturbance wavelength to jet diameter that can be used. Vibration amplitudes that favor secondary-drop formation must be avoided. In our example, which is typical, the disturbance wavelength (jet velocity/vibration frequency) is 0.021 cm, or 6 jet diameters. The peak jet-velocity modulation at the nozzle is about 70 cm/sec and results in drop separation at a point 0.13 cm downstream from the nozzle exit. Each drop has a diameter of 0.0073 cm and a mass of 0.2×10^{-6} g. Figure 3 is a photograph showing the drop-formation process.

DROP CHARGING

The drop-charging signal is applied between the metal ink-supply tubing, which contacts the ink flowing to the nozzle, and an electrode that surrounds, but does not touch, the jet at the drop-separation point. The signal potential establishes an axially symmetric electric field and corresponding charge at the surface of the unbroken column of conducting fluid extending from the nozzle. Neglecting the influence of charges on nearby free drops, the charge on a separating drop is equal to the product of the capacitance between drop and charging electrode and the charging potential at the instant of drop separation. Axial-velocity modulation of the drops by forces due to the charging field is small, because the charging potential is low compared with that establishing the deflection field. In our example, the computed capacitance between charging electrode and separating drop is 0.004 pF. A 1-cm drop deflection at the record surface requires a drop charge of 0.6×10^{-12} C and an input charging potential of 150 V. The input impedance equals the reactance of the capacitance—a few picofarads—of the charging electrode to the ink jet and ground.

A separating drop is also capacitively coupled to nearby drops just previously launched, and its charge is influenced to some extent by the charges on these neighboring drops. This drop-to-drop coupling modifies the high frequency response and results in an overshoot for a step change in input voltage. Typically, the overshoot has a magnitude of 20% and a decay time constant of 15 μsec. The frequency response may be equalized, and the overshoot may be eliminated, by preceding the input terminals with a simple RC network.

The foregoing discussion of drop charging assumes a perfectly conducting fluid and thus an equi-potential jet surface between nozzle and drop-separation point. For a fluid having finite conductivity, the "beam" current (0.06 μA for a drop charge of 0.6×10^{-12} C) causes a potential drop along the undivided jet between nozzle and drop separation point that must be subtracted from the input potential to obtain the effective drop-charging voltage. For transient inputs, the current that charges the capacitance distributed along the undivided jet must also be considered. The potential drop along the jet should be small compared with the input charging voltage, and the charge redistribution time on the jet, following a transient input, should be small compared with the drop repetition period. In a typical system, this requires that the ink resistivity not exceed several thousand Ω-cm. The ink actually used in our systems (Schaeffer's "Scrip") has a resistivity of 130 Ω-cm and the resulting potential variation along the jet is negligible.

ELECTROSTATIC FORCES

The deflection field traversed by the drops should be everywhere parallel to the record surface, so that drops having different charges will have the same transit time. If the only force on the drops in flight were exerted by such a field, each drop would follow a parabolic trajectory, and the impact point on the record surface would be displaced from the jet axis by an amount accurately proportional to drop charge. The magnitude of the deflection field is limited by the dielectric strength of air. It is made as high as possible, over as much of the drop flight path as possible, in order to minimize the drop charge required for a given drop deflection. However, the field cannot be maintained at the record surface, because the ink forming the record trace is a conductor. The deflection plates therefore do not extend all the way to the record surface, and edge effects

result in fringing and nonuniformity of the field in the region adjacent to the record surface. The result is nonlinearity in the deflection characteristic and an increase in drop transit time for large deflections.

Distortion caused by field fringing and by mutual electrostatic forces between drops is minimized by a long, flat trajectory and low drop charge. For a deflecting field of 16 kV/cm, the deflecting force (proportional to drop charge) on a drop with the typical charge (for a 1-cm deflection) of 0.6×10^{-12} C is 0.10 dyn. The corresponding mutual force (proportional to charge squared) between two drops with minimum spacing (0.021 cm) is 0.007 dyn. Gravity exerts the negligible force of 0.0002 dyn. In general, distortion caused by mutual forces determines the practical limit for drop charge rather than corona or deformation of the jet surface by electrostatic forces during drop formation and charging.

AERODYNAMIC DRAG

Although increasing the distance from nozzle to record decreases the charge required for a given deflection and hence the relative importance of mutual forces, it increases the distortion caused by aerodynamic drag. Associated with each drop in transit is a turbulent wake of disturbed air extending back along the line of flight, and a drop immediately following another experiences substantially less aerodynamic drag than does a drop traveling in still air. The decelerating force on a particular drop thus depends on the waveform being recorded and the position of the drop in that waveform. The resulting uncertainty in transit time increases with jet length and causes both time and amplitude errors in the record.

The maximum nozzle-to-paper spacing that may be used without serious aerodynamic effects is increased substantially by directing a stream of air across the space traversed by the drops, as shown in Fig. 1. The air flows in a direction perpendicular to the jet axis, and displaces the wake behind each drop so that it extends at an angle to the line of flight. Interference with following drops is reduced and, except for a constant displacement down the air-stream axis, each drop behaves as if it were traveling in still air. The air typically has a velocity of 750 cm/sec (about ½ of the jet velocity), and is carefully smoothed to minimize turbulence. In our example, the initial axial decelerating force due to air resistance is 0.11 dyn—about the same magnitude as the transverse electrostatic deflecting force. Air drag decreases the axial component of drop velocity from the initial value of 2100 cm/sec to about 1300 cm/sec at impact. The corresponding transit time for the 3.5-cm journey is 2.1 msec.

DISTORTION

System fidelity is determined by: (1) uniformity and short-term stability of the mass, initial velocity, and charging geometry of the ink drops; and (2) variations from the ideal drop trajectories during flight resulting from deflection-field fringing, aerodynamic forces, and mutual electrostatic forces. It turns out that system distortion is dominated by the defects listed in (2), which are associated with forces acting on the ink drops during flight, and not by defects in the launching and charging processes. Recording fidelity is thus principally determined by the geometry of the flight path and deflection system, the aerodynamic Reynolds number, and the relative magnitudes of the aerodynamic forces, mutual electrostatic forces, and deflection forces that act on the drops during flight.

The typical parameter values given are appropriate for a system having a 100-kc drop-repetition rate and a maximum peak-to-peak deflection, without serious distortion, of 2 cm. To obtain a greater undistorted deflection, a larger system is necessary, having a lower drop-repetition rate. Conversely, to increase the drop-repetition frequency, the dimensions of the system, including the maximum deflection, must be reduced. For systems not differing too much from the one described, the product of drop-repetition frequency and maximum deflection amplitude is approximately constant.

FREQUENCY RESPONSE

The full-scale transient-response time of the oscillograph equals the drop-repetition period—10 μsec in our example. The corresponding frequency response is not so easily defined. The oscillograph constitutes a sampled-data system, with a sampling rate equal to the drop-repetition frequency—typically 100 kc. According to Shannon's[18] sampling theorem, the frequency response extends to one-half the sampling frequency (i.e., to 50 kc), provided the input-signal frequency is band-limited to that value. However, the discontinuous sampling process and presentation make the interpretation of high frequency records difficult, and result in a usable frequency response that may be much less than theory indicates, depending on the particular application.

INTENSITY MODULATION

A collector is interposed between nozzle and paper, as shown in Fig. 1, to intercept ink drops having a deflection just exceeding that produced by the maximum signal. The quantity of ink forming the recorded trace may then be reduced by charging the ink drops with a pulse train that is amplitude-modulated by the signal to be recorded. The width of each pulse is made just sufficient to charge one ink drop, and the pulse-repetition frequency is made equal to the desired ink-drop delivery rate. The charging signal

[18] B. M. Oliver, J. R. Pierce, and C. E. Shannon, Proc. IRE 36 1324 (1948).

is biased so that drops charged by the pulse peaks form the record trace, while drops having a charge corresponding to the pulse baseline voltage are intercepted by the collector.

To avoid deflections corresponding to the raising and falling portions of the pulses, signal sampling (drop separation) must not occur during the transition intervals. The pulses are therefore synchronized with the drop-forming signal (nozzle-vibration-transducer input) and phased so that drop separation occurs at the center of each pulse and not during the transitions between pulse peak and baseline. Proper operation requires appropriate stability for all the parameters that influence the phase relationship between the drop-forming signal and the drop-separation time.

PERFORMANCE

For a system having a 100-kc drop rate and a maximum peak-to-peak record amplitude of 2 cm, the maximum deviation from a linear deflection characteristic is about $\pm 5\%$ of this full-scale amplitude. Accuracy along the time axis is limited by variations in ink transit time to about ± 25 μsec.

Performance of typical experimental systems is illustrated by the oscillograms reproduced full size in Fig. 4. The 10-cps square-wave record of Fig. 4(a) was written with 2000 ink drops per sec. The good resolution at the low (17-cm/sec) chart speed results from interception in transit of 98% of the 100 000 drops launched per second. Figure 4(b) shows a 1-kc damped-sine-wave record for which drop interception was determined automatically by circuits controlled by the signal derivative. The drop-repetition rate at the record surface varies from a minimum of 4 kc at zero signal to a maximum of 50 kc at maximum signal slope. This derivative-control technique permits high frequency signals to be recorded at low chart speeds without blurring the trace with surplus ink when the signal fluctuations are small.

Figures 4(c) through 4(e) show records of equal-amplitude sine waves, having different frequencies, taken at the same chart speed and a drop-repetition frequency of 80 kc. No ink was intercepted. The high frequency capabilities and shortcomings of the system, resulting from the discrete sampling process, are evident. Figure 4(f) shows a 10-kc sine-wave record taken with a smaller, higher frequency system having a drop-repetition frequency of 174 kc.

APPLICATIONS

This technique should be capable of development into a practical oscillograph having advantages found in no other currently available system. Recorders with a multiplicity of channels are easily arranged, with several

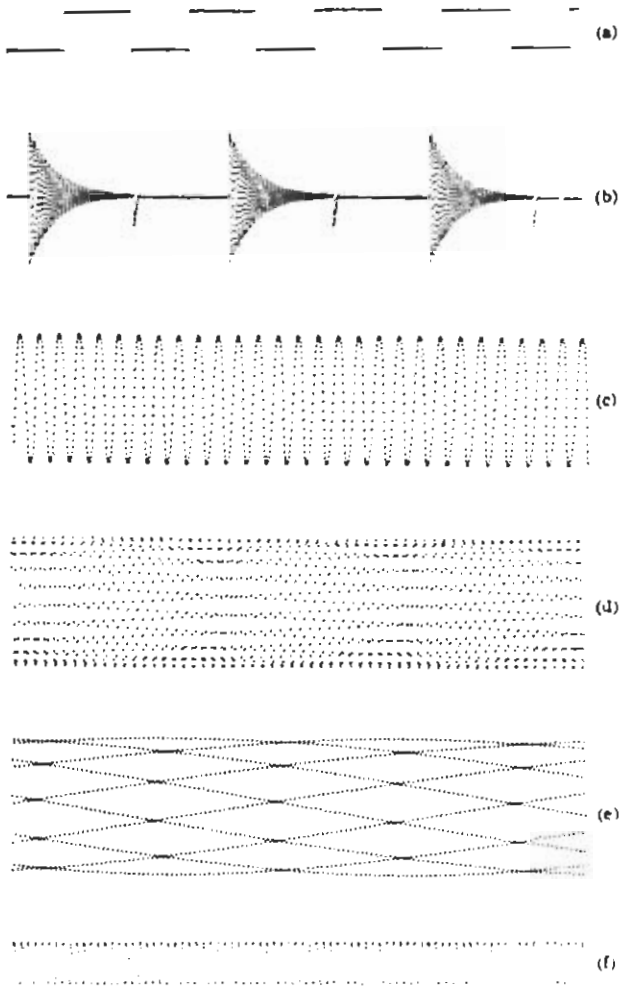


FIG. 4. Representative oscillograms, (a) 10-cps square wave, (b) 1-kc damped sine wave, (c) 2-kc sine wave, (d) 4-kc sine wave, (e) 8-kc sine wave, (f) 10-kc sine wave.

channels sharing a common deflection system. Traces may cross without interference, and channel identification can be facilitated by the use of colored inks. With respect to deflection amplitude and accuracy, the system performance is inferior to that achievable with optical oscillographs—the technique is, therefore, most useful in high frequency applications requiring only moderate precision, but where convenience and operating economy are important.

Extensions of the technique should be applicable to high speed printing and facsimile systems. In systems requiring only on-off control, and not analog deflection, the drop flight path need be shifted very little to transfer between marking and intercepted trajectories. Very small jets with drop-formation rates substantially higher than those appropriate for oscillographs might then be practical. Jets arranged in closely spaced arrays, using a common deflection field, could be independently controlled to provide information-recording rates well into the megacycle range.

The absence of physical contact or critical spacing between the ink-launching mechanism and the record surface suggests applications in marking or labeling of rough or curved surfaces, or surfaces sensitive to pressure. More general applications include the precise high speed control of any kind of low volume fluid flow. The technique could be used to accurately dispense or deposit any solid substance that is soluble in a conducting-fluid vehicle, or that is sufficiently fluid and conductive when molten.

ACKNOWLEDGMENT

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H-4 February 25, 1966

Mr. Richard Sweet
Stanford Electronics Laboratories
Stanford University
Stanford, California

Dear Mr. Sweet:

Dr. Leonard Herzenberg in the Department of Genetics of Stanford Medical School has a set of drawings of the droplet generator system. I understand that he is beginning to construct a separator.

I do not attempt to avoid formation of satellite droplets; as long as they recoalesce quickly, they do not affect the separation efficiency. Stabilizing the length of the fluid jet is of concern, but after a few minutes of operation this length is fairly stable.

As you will see from the blueprints, a good deal of effort has gone into features secondary to droplet formation such as the flushing system, removable apertures, etc. The latest design will, hopefully, withstand autoclave sterilization.

We are pressing biological applications of the device as quickly as time and personnel permit. We are also investigating optical particle sensors with the hope of measuring optical characteristics of cells and separating on this basis.

Unfortunately, I am unable to give you the drop-to-drop spacing, etc., which you requested. I fear I have lost the record of operating conditions at which these photographs were taken.

Perhaps I will be able to see you next time I am in Palo Alto. If you are ever in this area, please plan to visit us; I am sure you would find our work interesting.

Is your ink writing oscillograph patented in such a way that this must be considered by a commercial company manufacturing the cell separator?

If, after talking to Dr. Herzenberg, you have questions, please feel free to write.

Sincerely yours,

Mack J. Fulwyler

MJF:ES
Enc. sketch