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UNIFORMLY CONDUCTIVE SURFACES

By

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SUMMARY

This report evaluates materials available for making conductive plates which can be used in setting up electrical analogs to various problems, and describes an investigation of the use of conductive paint to make such plates.

The paint studied produces plates satisfactory for many purposes but not sufficiently uniform for trajectory problems.

UNIFORMLY CONDUCTIVE SURFACES

Electrically conductive plates having a uniform resistivity can be used to provide an electrical analog for many physical problems. The present investigators are, however, principally interested in using them to study the trajectories of particles in a fluid flow medium as described in Reference 1.

The properties which a sheet must have in order to be useful in this application are as follows:

1. It must have a resistivity intermediate between good conductors and good insulators. This is necessary because other parts of the analog system must be conductors having a resistivity much lower than that of the conductive sheet, while still other parts of the system must have a resistivity which is much higher than the conductive sheet. The range of resistivity which is acceptable for this application lies roughly in the range from 100 ohms per square to 100,000 ohms per square.

2. The resistivity must be uniform throughout the conductive sheet. This is an especially critical property for the application to trajectory problems because it is necessary to measure the potential gradient at points on the conductive sheets. Since it is such an important property it will be worthwhile to discuss the way in which it is measured. Electrodes are attached to two opposite edges of a rectangular piece of the conductive sheet. The other two edges are terminated in good insulators. With a constant voltage between the two electrodes, the potential difference is measured between two prongs of a probe which touch the conductive sheet. The two prongs are lined up in the direction of current flow and are about one-tenth of an inch apart. Ordinarily the potential difference is measured between the two prongs at many points on the conductive sheet and the percentage variation of the voltage reading is taken as a measure of the uniformity of the conductive sheet.

3. The conductive sheet must have a surface which is sufficiently hard so that it will not be damaged by the abrasion of probes sliding over it.

4. The temperature coefficient of resistance of the plates must be small to prevent their resistivity from changing when they are heated by the current which passes through them.

5. The conductive sheets must be dimensionally and electrically stable so that their properties will not change over a period of several weeks.

6. The sheets must be available in a size approximately 20 inches square.

EVALUATION OF SOME MATERIALS FOR CONDUCTIVE SHEETS

A number of materials were considered for suitability as conductive sheets. A brief evaluation of these follows:

1. Commercially available metal foils have too low a resistivity for use.

2. Glass plates which have a thin coating of metallic oxide are available commercially. The coatings have low temperature coefficients, and are strong and stable, but have resistivities at the extreme lower end of the acceptable range. One piece of "Nesa" glass manufactured by the Pittsburgh Plate Glass Company had plus or minus fifteen percent variation in resistivity. This is considerably less uniform than is required for application to trajectory problems. Glass coated with metallic oxides shows some promise of making a satisfactory material for conductive surfaces.

3. Electrolytic conductors can be used to form a conductive sheet. In using them, however, it is necessary to use an alternating current system to prevent polarization of the electrolyte. The electrolyte might be impregnated in a paper or ceramic, or a fluid electrolyte might be contained in a nonconducting tank. Promising results have been obtained by Research Incorporated, using an electrolytic tank.

4. A conductive carbon-coated paper can be procured commercially under the trade name "Teledeltos" paper. The paper has a resistivity of approximately 8000 ohms per square which is satisfactory for trajectory

computations. The uniformity in resistivity of this paper is about plus or minus 7 percent, although selected sections of the paper may have smaller variations. The Teledeltos paper does not have isotropic resistance characteristics, the resistance in different directions varying by approximately 15 percent. This paper is rather easily scratched and torn by the traverse of the contacting probes.

5. Conductive sheets of plastic have been prepared by the addition of graphite fillers in the process of manufacture. Such plastics usually have a nonconductive surface which must be machined away before they can be used in any application such as is considered here. These materials have a uniformity of resistivity of approximately plus or minus 10 percent.

6. Conductive plasters can be made by adding carbon pigments to the ingredients. Investigations of this material revealed several hundred percent variation in the local resistivity. In addition, the surface of this material broke down under the abrasion of the probes. This material has little promise of being developed into a suitable conductive sheet.

7. Electrically conductive paint can be made by adding conductive pigments in its formulation. This offered a promising approach to the formation of uniformly conductive surfaces, and a more extensive investigation of this material was instituted, which is described in the next section.

FORMATION OF UNIFORMLY CONDUCTIVE PAINTED SURFACES

The problem of developing the uniformly conductive painted surface can be conveniently divided into two parts, that of formulating a paint with a uniform conductivity and that of applying such a paint with a uniform thickness over some base material. Since the properties which the fluid paint must possess will depend to a large degree on the method of application, a study was first made of the problem of uniform application.

The ASTM recommends several procedures for the production of uniform-thickness paint coating (2). One of these employs a doctor blade, which is a straightedge supported by shims at the two ends. A puddle of paint is placed on the base material and the blade is drawn across, leveling the puddle of paint into a uniform film. This technique was satisfactory for producing uniformly thick films, two to six inches wide. However, when an attempt was made to make plates about 18 inches wide, difficulties were encountered in obtaining base materials sufficiently level and flat so that the gap between the doctor blade and the base material remained constant.

The ASTM also suggests a method of making a uniform coating by means of an automatic spraying machine. A first attempt at using this method consisted in spraying a dispersion of colloidal graphite onto a sheet of tracing paper fastened to a rotating drum. The paint was applied with a spray gun which traversed along the drum normal to the direction of rotation. This technique produced fairly uniform coatings, but the surfaces of these coatings were unsatisfactory in that the paint did not adhere well to the paper and the paper tore rather easily. Substituting other papers for the tracing paper produced no improvement.

Another attempt was made spray painting a lacquer dispersion of colloidal graphite onto plexiglass sheets. The lacquer-based paint produced much better adhesion but the uniformity of conductivity was poor. Since this poor uniformity might be due to the interaction between the lacquer solvent and the plexiglass sheet, plate glass was substituted for the plexiglass. The spray gun was moved across a glass plate in a pattern, as shown in Fig. 1, so that a uniform application of paint would result through the averaging of several coats.

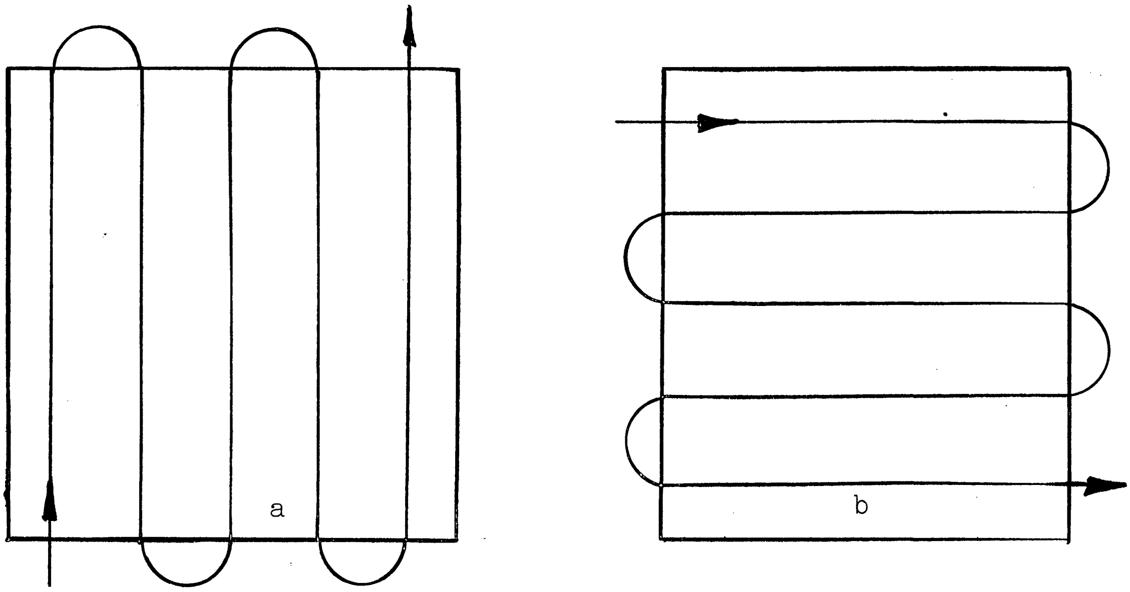


Fig. 1. Method of application of conductive paint spray to square plates. (a) first coat, (b) second coat, etc.

The paint adhered well to the glass and the paint surface was strong enough to withstand the abrasion of metal probes fairly well, but the conductivity uniformity over 18-inch by 18-inch plates showed a variation of as much as 20 percent in some cases, and usually a variation of 5 to 10 percent. Since this was insufficient uniformity, a third method suggested by the ASTM was tried, namely, automatic dipping. H. F. Payne has published results (3) which also indicate that automatic dipping is an effective way of producing a uniform paint film. Figure 2 is a reproduction from his publication.

The dipping technique requires apparatus which can withdraw a panel from the liquid paint at a constant rate and with a motion entirely free from vibration. Generally, withdrawal rates of 2 to 4 inches per minute are most satisfactory. The following procedure and apparatus were used to dip coat the glass plates.

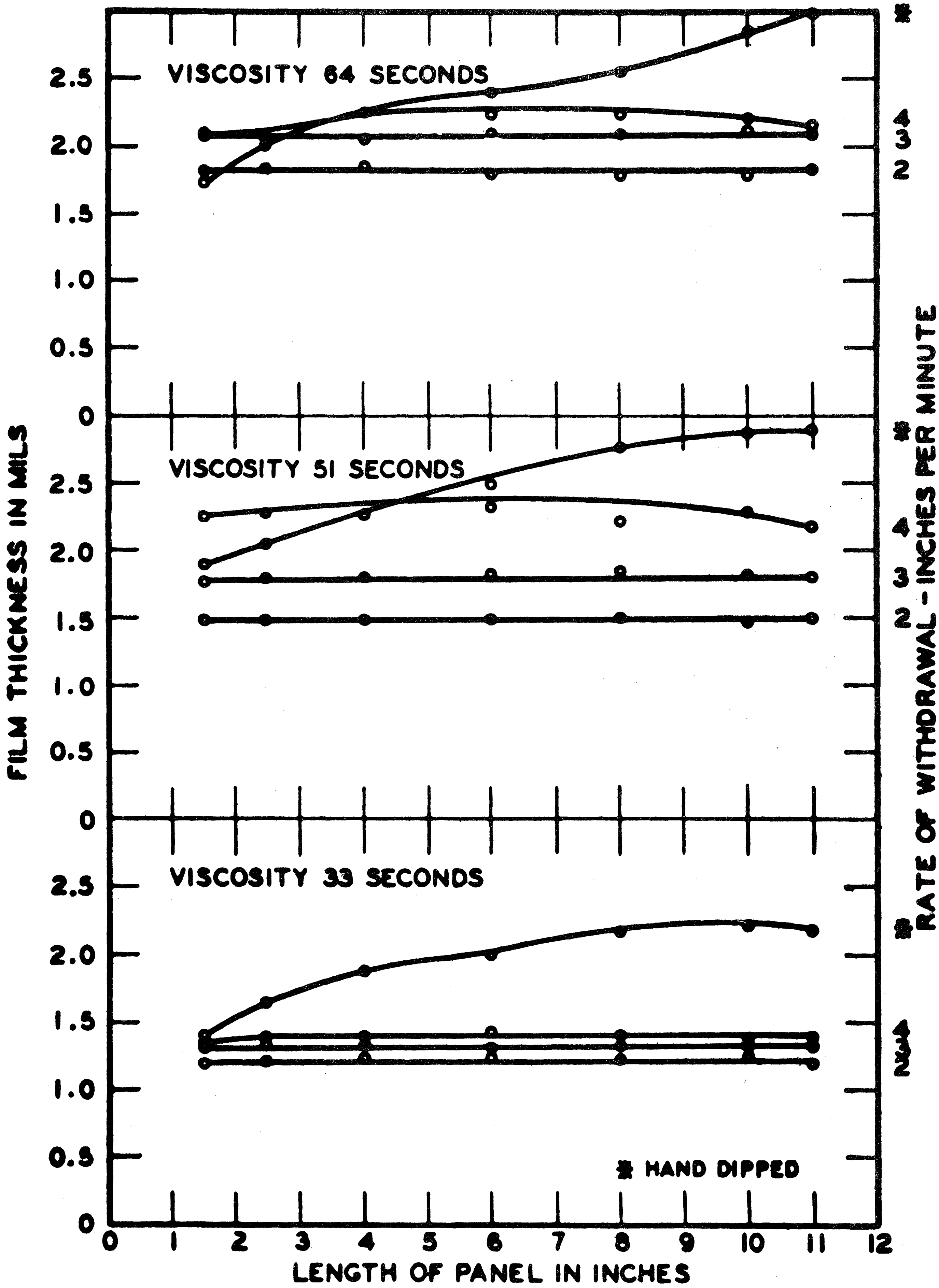


Fig. 2
(Reference 3)

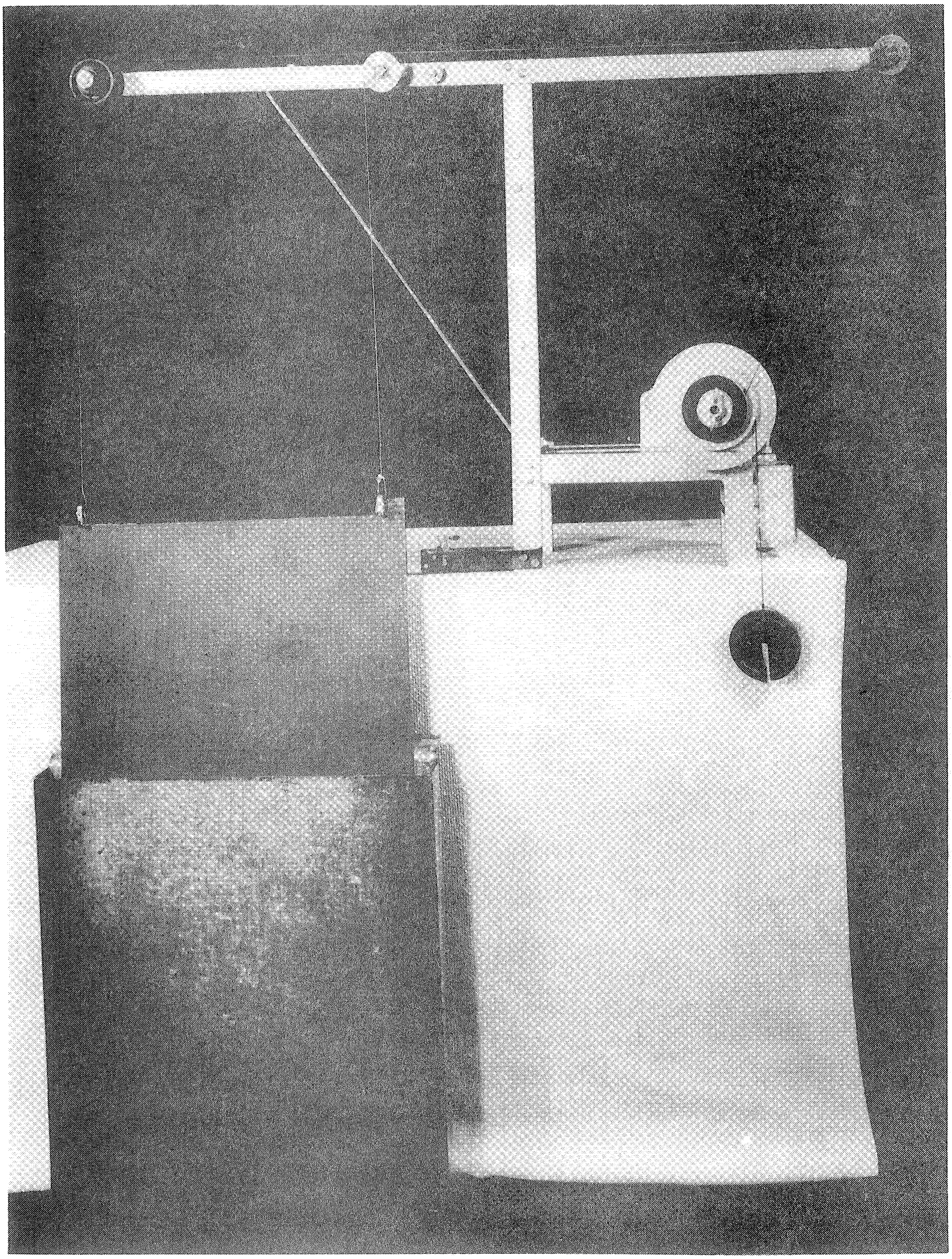


Fig. 3. Apparatus for Dipping Glass Panels

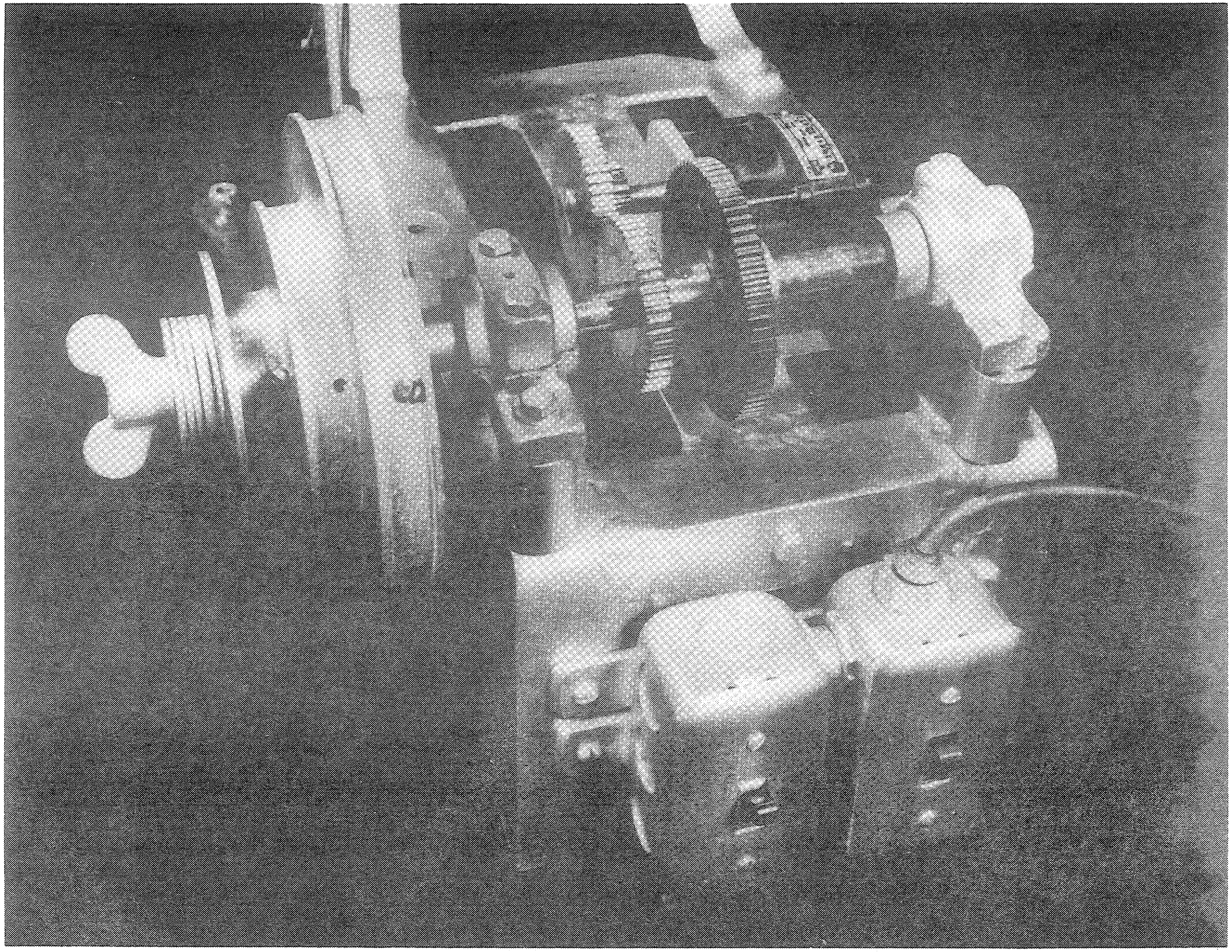


Fig. 4. Motor and Gears for Dipping Glass Panels

A piece of plate glass, which had previously been cleaned with a water-detergent solution, and then with butanol, was supported on the ends of two metallic cords as shown in Fig. 3. The metallic cords passed over the pulleys and were wound up on the large motor-driven pulley. The steps on the driving pulley made possible withdrawal rates of 2, 4, or 6 inches per minute. A small synchronous motor drove the pulley through a transmission which permitted the panel to be lowered into the paint tank at a faster rate than that used for withdrawal. A counterweight, shown in Fig. 3, was used to reduce the load on the motor. Figure 4 shows the driving pulley, motor, and transmission.

It was necessary to take special care to prevent any vibrations while a plate was being withdrawn. Vibrations caused by people walking around the room or by air currents produced waves in the dipping bath, which in turn produced nonuniformities in the conductive surface. When the proper precautions were taken to prevent vibrations, the dipping process gave more uniform coatings than any other method.

THE FORMULATION OF A CONDUCTIVE PAINT

A plan for formulating a conductive paint was to add conductive pigments to the paint in the expectation that the resistivity of the paint coating could be controlled by the amount of pigment added. There are several brands of conductive paint containing silver pigment on the market. (4, 5). These, however, yield conductive coatings the resistance of which is too low. In an early investigation it was discovered that paints containing standard grades of aluminum or copper pigments yielded nonconductive coatings, whereas paints containing carbon black or graphite as the pigment filler yielded conductive coatings in which the conductivity varied with the amount of filler added. After further experimentation, a specific formulation was developed for a paint which has reasonably good electrical properties and dries in about 5 minutes when it is applied by dipping. The paint consists of two basic mixtures, a graphite dispersion and resin mixture. The formulations for each of these is given in Table I. By varying the ratio of the two components, the resistance of the paint film can be controlled as shown in Fig. 5.

In the paint made by this process there occurs segregation of pigment particles on the surface of the liquid paint which is commonly called "floating". In order to prevent the floating pattern from being transferred

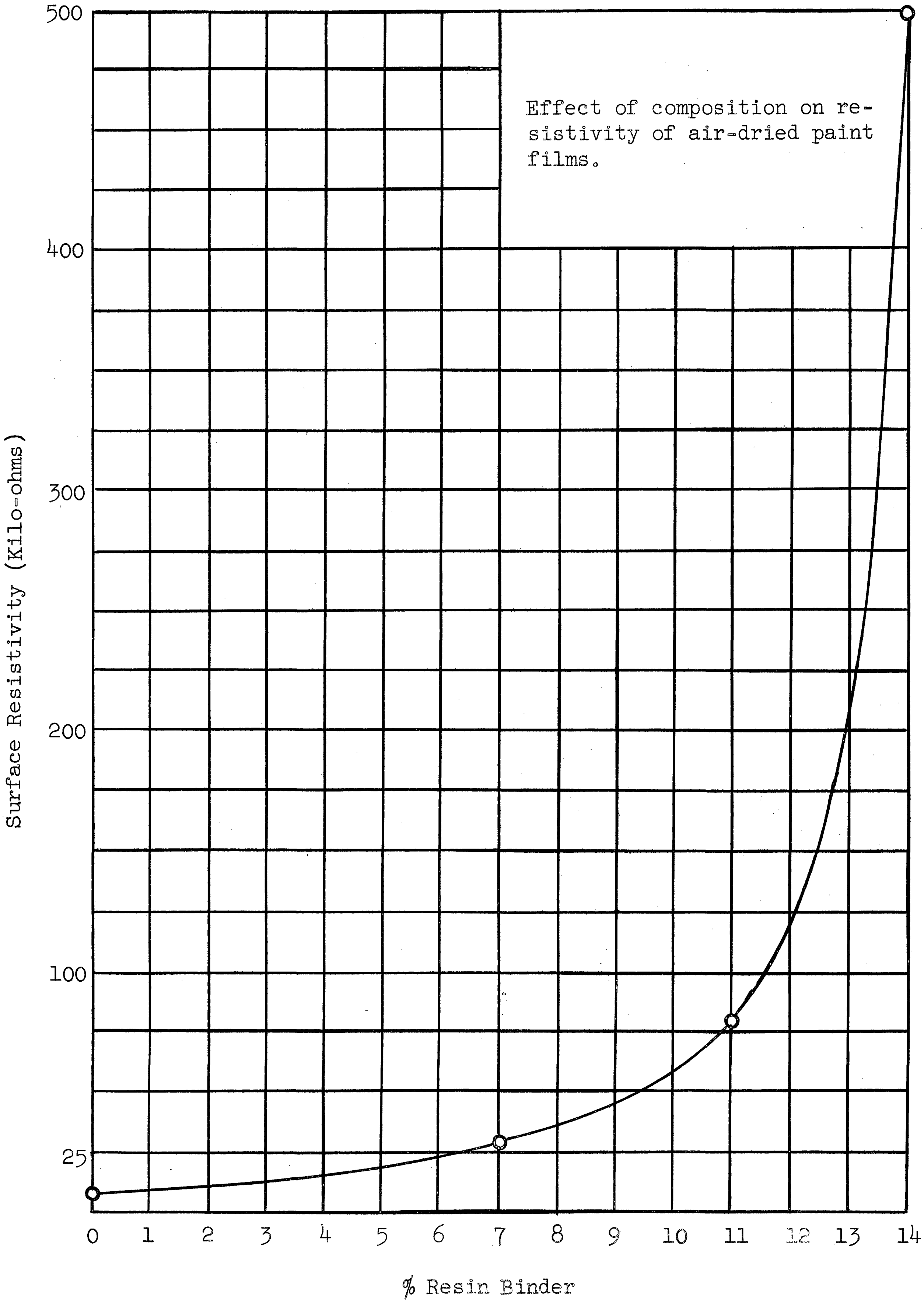

Effect of composition on resistivity of air-dried paint films.
Surface Resistivity (Kilo-ohms)
500
400
300
200
100
25
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14
% Resin Binder

Fig. 5

onto the glass, it is necessary to sweep it away by drawing a glass rod across the surface of the paint immediately before the glass panel is immersed.

TABLE I

Resin Binder (Parts by Weight)		Supplied by
1300	Beckosol P-373	Reichhold Chemicals Inc., Detroit
30	24% Pb Naphthenate	Nudex Products Inc., Elizabeth, N.J.
12	6% Co "	" "
120	6% Fe "	" "
27	8% Zn "	" "
23	Active - 8	R. T. Vanderbilt Co. Inc., New York
108	Petroleum thinner	

Graphite Suspension		
1320	Dag 194	Acheson Colloids Co., Port Huron, Mich
290	Dag 38	" "
200	Federal Specification Conductive Paint (MIL-E-16583)	Glidden Co., Cleveland, Ohio
35	Furnex Carbon Black	Binney and Smith, New York
15	Natural Graphite	U. S. Graphite Corp., Saginaw, Mich.
8	Lecithin	Glidden Co., Cleveland, Ohio
6	Anti-Floating Agent	Lilly Varnish, Idianapolis, Ind.
15	Petroleum Ether	

Mix components by grinding 72 hours in ball mill.

An air-dried film made from the above paint is rather susceptible to scuffing from abrasion of the probes. The hardness and toughness of the paint film can be increased considerably by baking the film for one quarter hour at 200°F. Such a baking, however, lowers the electrical resistance of the paint film in a rather erratic way. Table II gives an indication of how the resistance of painted panels varies with their baking treatment. Some of the data of Table II are for a paint film similar to ours, but over which no control has been exercised to produce a uniform coating.

TABLE II

THE EFFECT OF BAKING ON THE ELECTRICAL RESISTANCE OF PAINT

Temp of Baking, °C	Resistance, Air Dry	- Resistance after Baking - 1/4 hr.	1/2 hr.	1 hr.	2 hr.	3 hr.	Reported by
93	85,000	50,000	—	—	—	—	U M Icing Research
93	500,000	50,000	—	—	—	—	"
60	850,000	720,000	660,000	600,000	580,000	480,000	Acheson Colloids Corp
100	600,000	67,000	56,000	46,500	35,000	32,000	
140	660,000	10,900	9,000	7,500	6,900	6,300	"
180	460,000	2,180	2,100	1,900	1,740	1,550	"
220	590,000	1,520	1,420	1,060	850	710	"
260	580,000	700	520	400	265	183	"
300	550,000	270	136	138	120	100	"
340	430,000	79	65	69	67	63	"
380	320,000	62	88	111	185	3,400	"

TESTING THE CONDUCTIVE PANEL

Figure 6 shows the results of a test of a painted panel. The conducting electrodes are at the top and the bottom of the plate. A battery maintains the potential difference between the electrodes at 135 V. The double-pronged probe is placed at the points indicated by the circles, and the voltage difference is measured between the prongs. The readings thus taken appear in the circles.

The highest and lowest readings were .99 and .87, respectively. This is equivalent to a uniformity of plus or minus 6.5 percent, which is typical of that obtained with these plates, although sometimes the uniformity is considerably worse.

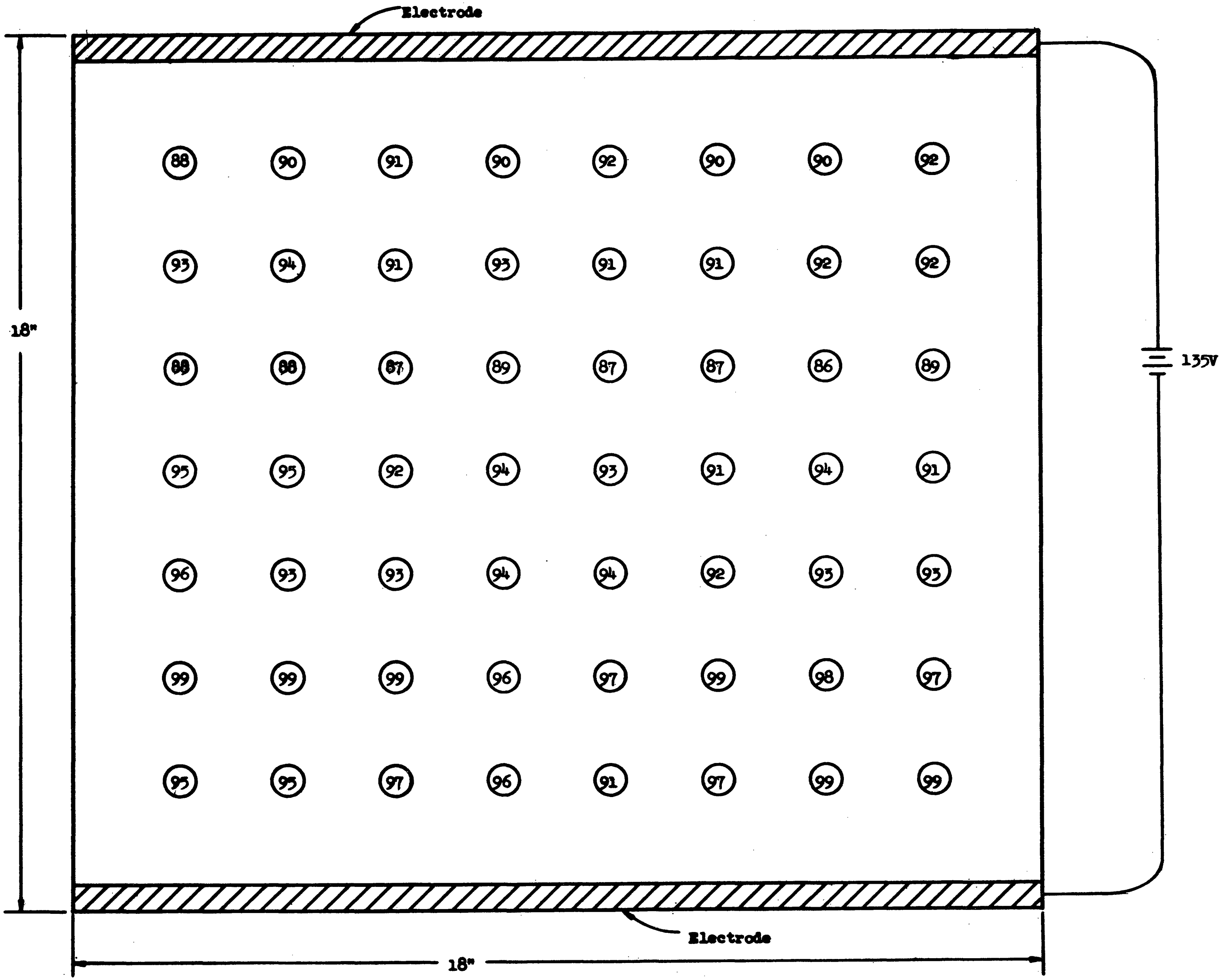
Figure 7 shows a continuous plot of the voltage gradient along a path which crosses the plate. The arrangement of the electrodes is the same as shown in Fig. 4.

An attempt was made to examine the paint film microscopically to see if the cause of the non-uniformity could be determined. It was not possible to remove a suitable piece of paint from a glass panel, but a specimen was prepared from a piece of plexiglass which had been dip coated. Fig. 8 is a photo-micrograph of this specimen. The paint film is about 0.0002 inches thick and a light microscope reveals no details of its structure.

The uniformity of these painted surfaces is marginal for the problems in trajectory computation. It would be necessary to check each plate for uniformity of resistance, since only the best could be used. The painted plates are, however, extremely convenient to work with and might be satisfactory for other problems which have less stringent requirements on uniformity.

APPLYING BOUNDARY CONDITIONS TO PAINTED GLASS PLATES

When conductive plates are used in analog computations, it is first necessary to put electrical boundaries on the plates which are analogous to the boundary conditions of the problem. For fluid flow in potential motion there are two types of boundaries. In the first type, the velocity potential has a constant value; the second type follows the streamlines of the flow. Correspondingly, on the conductive plate there are two types of boundary. The first is an electrically conductive boundary which is maintained at the same electrical potential throughout. The second kind is an insulating boundary across which no electrical current can flow.



Test of Painted Panel

Figures in circles are proportional to voltage gradient at the point.

Fig. 6

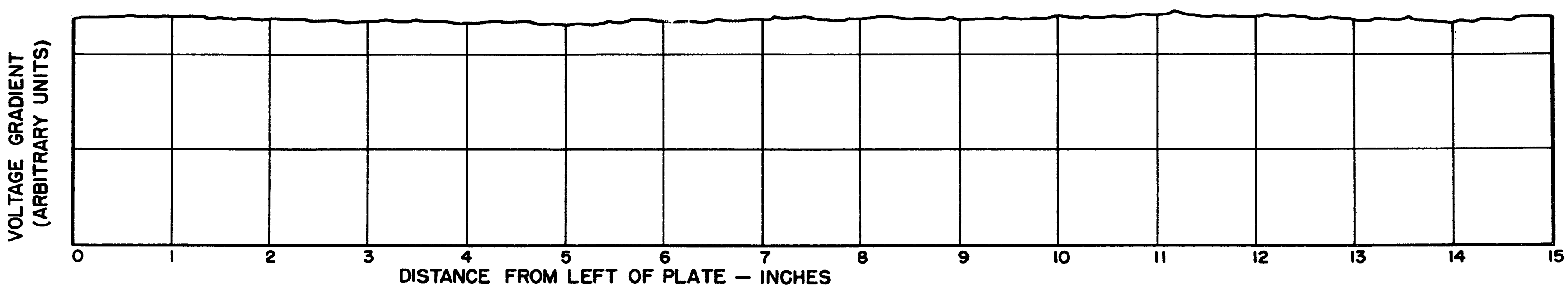


Fig. 7

Variation of Voltage Gradient on Painted Glass

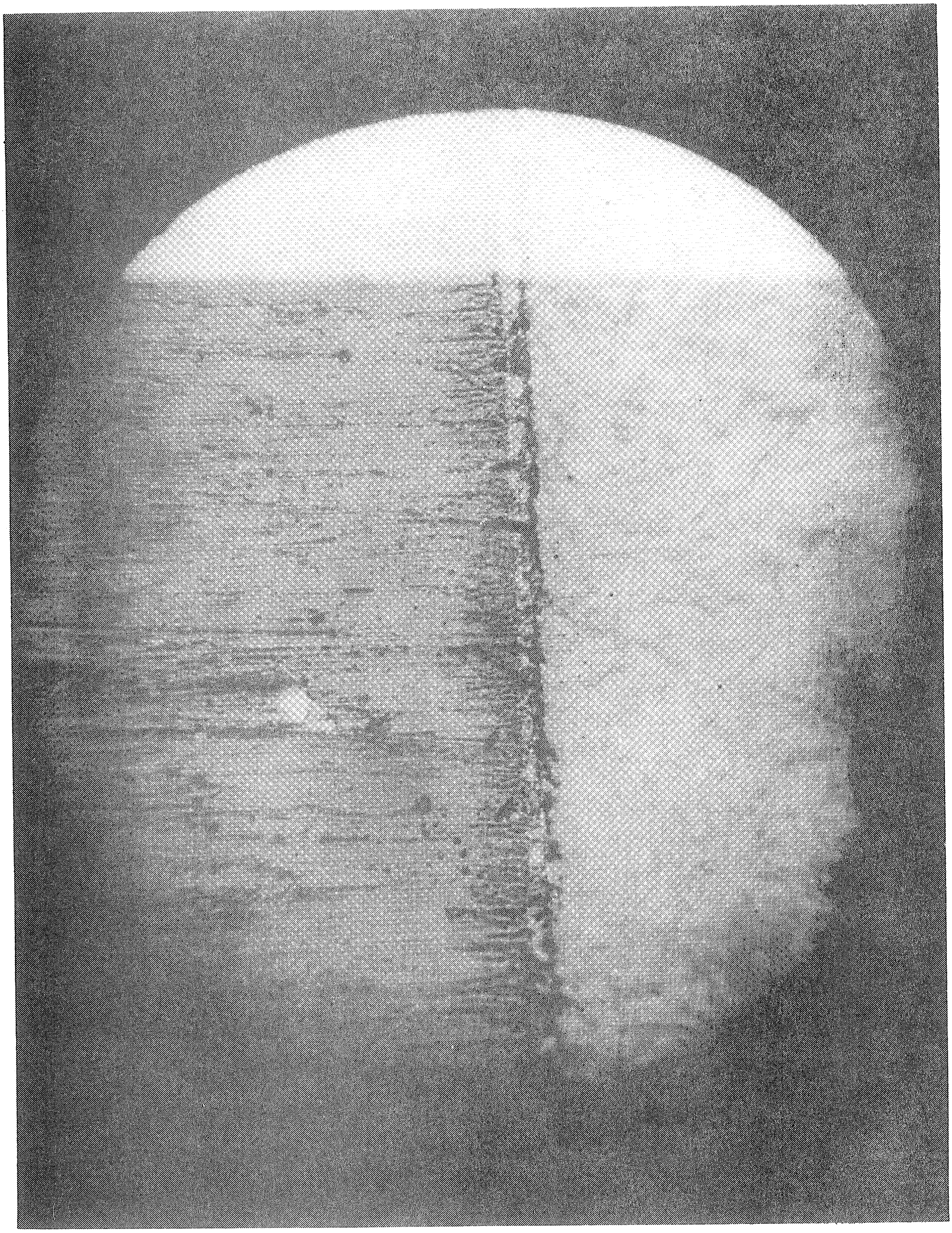


Fig. 8. Photomicrograph of Paint Film

This is a cross-section view. The small band remaining vertical is the paint film. (1000x)

Either type of electrical boundary can be made to correspond to the streamline boundary in the fluid flow with the remaining type of boundary corresponding then to the equipotential lines in the flow. In the examples which follow, the electrical equipotential lines are equivalent to the streamlines. The insulating boundary will therefore be analogous to equipotential lines in the fluid-flow field.

Conductive boundaries can easily be put on the painted glass by applying a conductive silver paint with a small brush. This paint is used for electrical circuits and is available commercially under several brand names. (4, 5). The insulating boundaries for the conductive surface can be made by scraping off the graphite paint with a knife or razor blade.

EQUIPMENT FOR SOLVING TRAJECTORY PROBLEMS

The plotting table used for solving trajectory problems and in which the conductive plates are mounted is shown in Fig. 9. Fig. 10 is a larger view of the probe which makes electrical contact with the electrical plate. The probe here shown has three prongs on it, so that it can be used to obtain the voltage gradient in two directions.

One problem which can be solved with the aid of the conductive plate is that of tracing the streamlines in a fluid-flow field. Fig. 11 shows the wiring diagram of the plates and plotting table. When the probe is moved from one side to the other in the x-direction it traces a streamline across the plate. The path of the probe can be recorded on auxiliary apparatus or, since the probe leaves a slight mark on the plate as it passes across it, the streamline can be obtained by examining the plate itself. Fig. 12 shows the streamlines around a cylinder obtained by this method.

A more complicated problem requiring a multiple-prong probe is the calculation of the trajectory of a particle in a fluid-flow field. The method of solution of this problem is given in Reference 1. Fig. 13 shows the trajectory for a particle in a hyperbolic-flow field as calculated with a painted glass plate. For this particular problem an analytic solution is available and this is shown for comparison on the same plot.

It can be seen that the plates give only a fair solution to the problem. In evaluating the plates it should be remembered, however, that trajectory problems require greater plate uniformity than most others. The plates are very convenient to use and may be sufficiently uniform for many other analog computations.

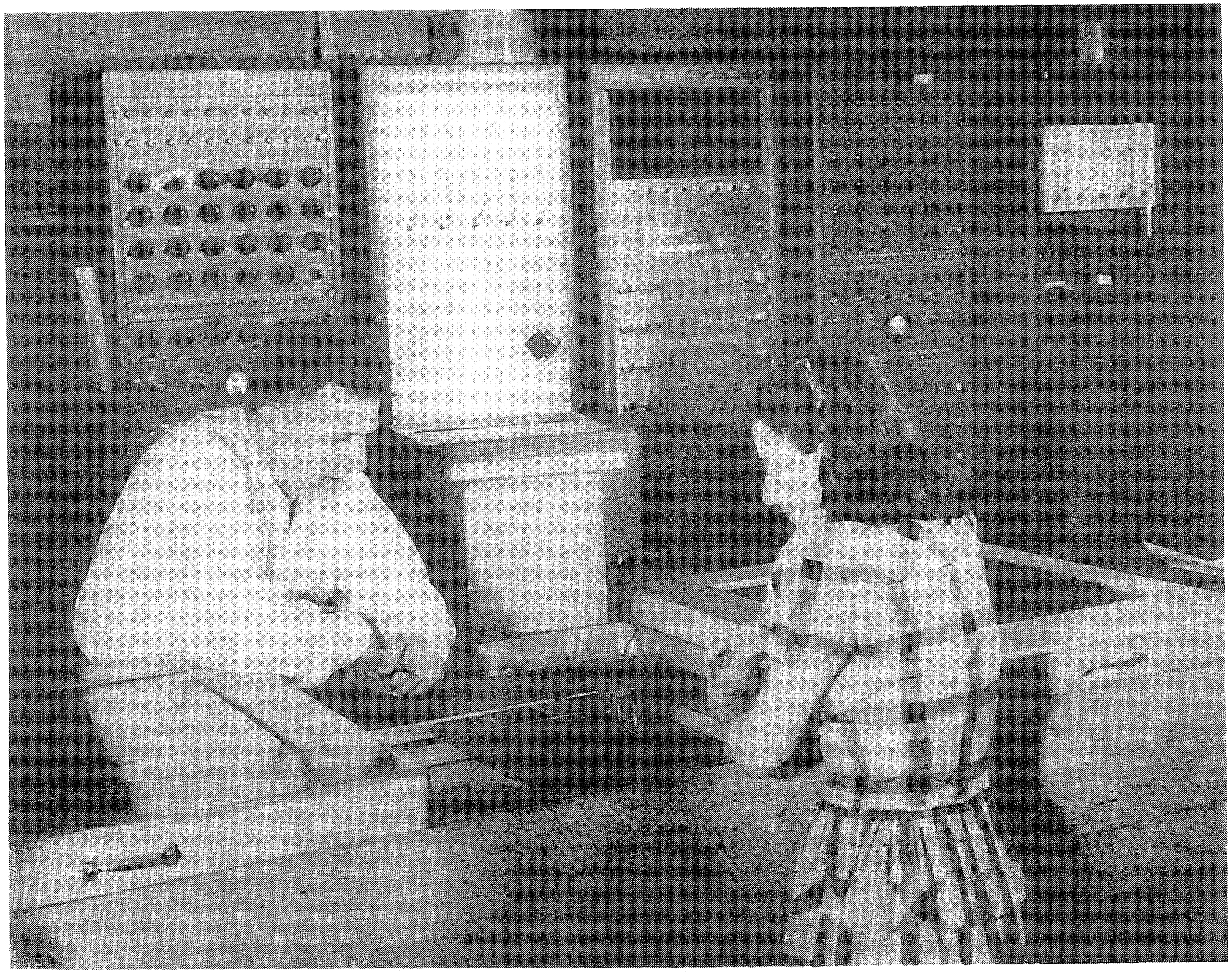


Fig. 9. The Plotting Table in Use

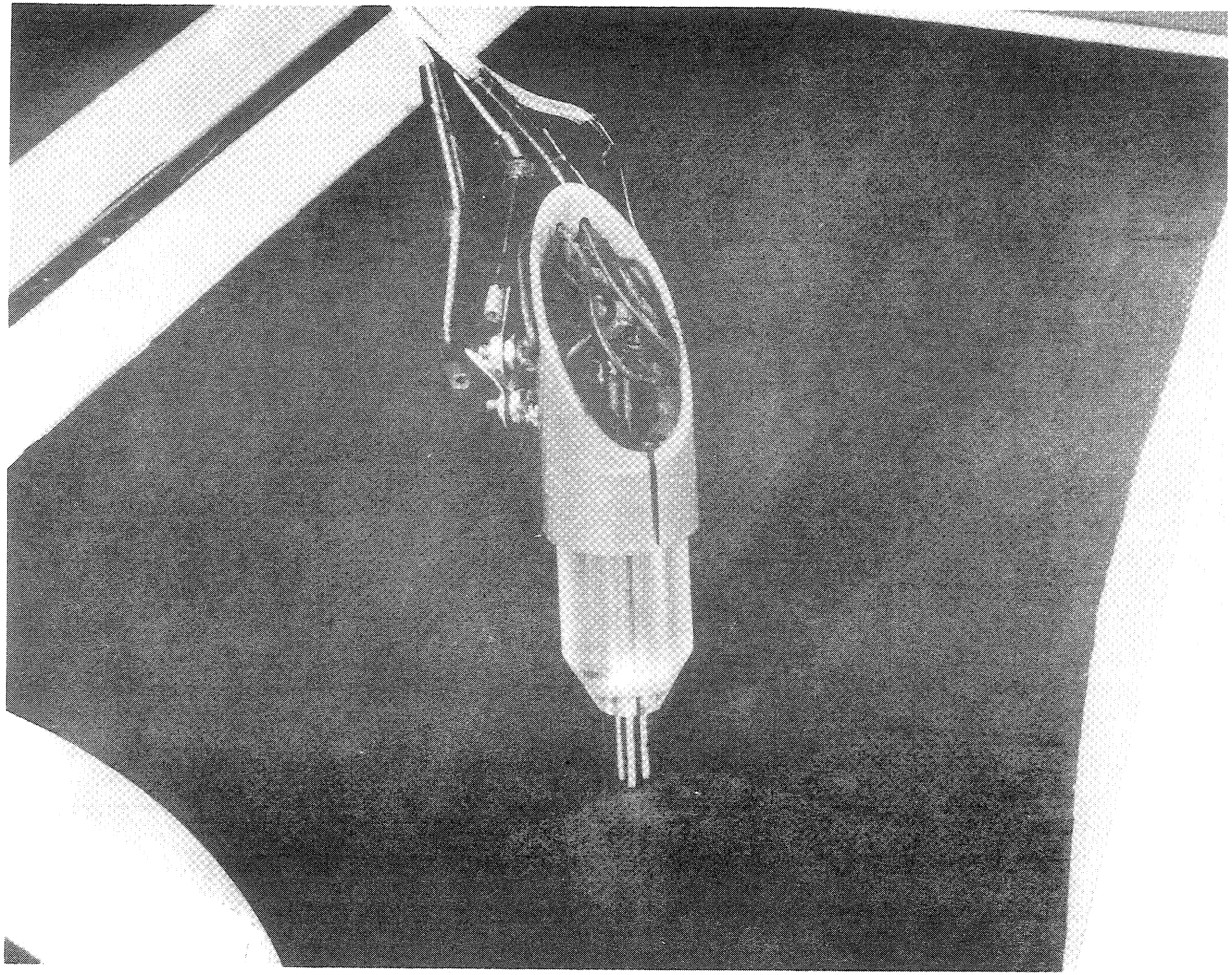


Fig. 10. A Close-Up View of the 3-Prong Probe

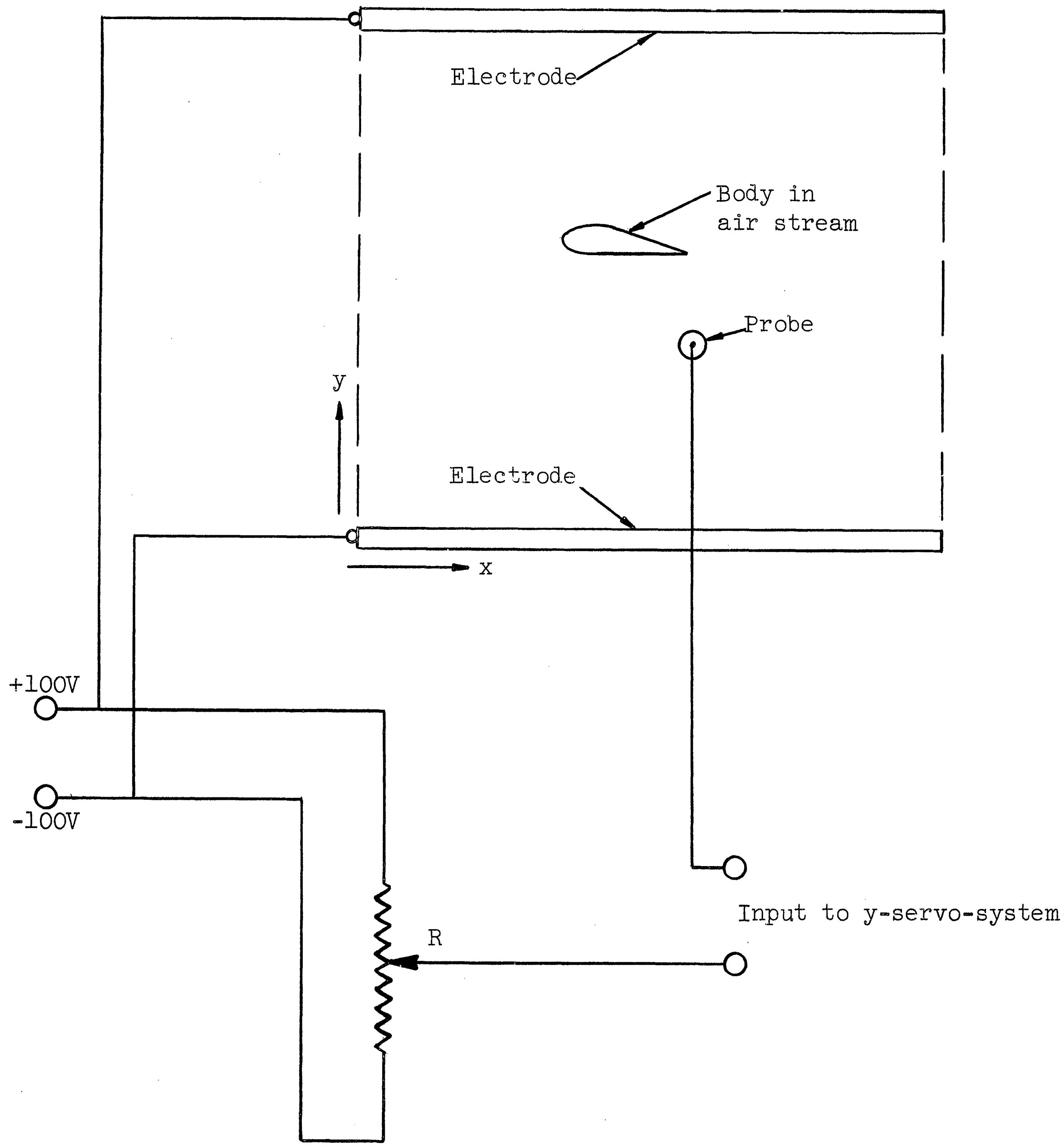


Fig. 11. Circuit for tracing streamlines.

The x-coordinate of the probe is increased continuously. Meanwhile the y-servo-system moves the probe in the y-direction in such a way that the probe always stays at the potential set by R. Thus, the probe traces an equipotential line which corresponds to a streamline in the flow field. Another streamline can be obtained by repeating the procedure with a different value of R.

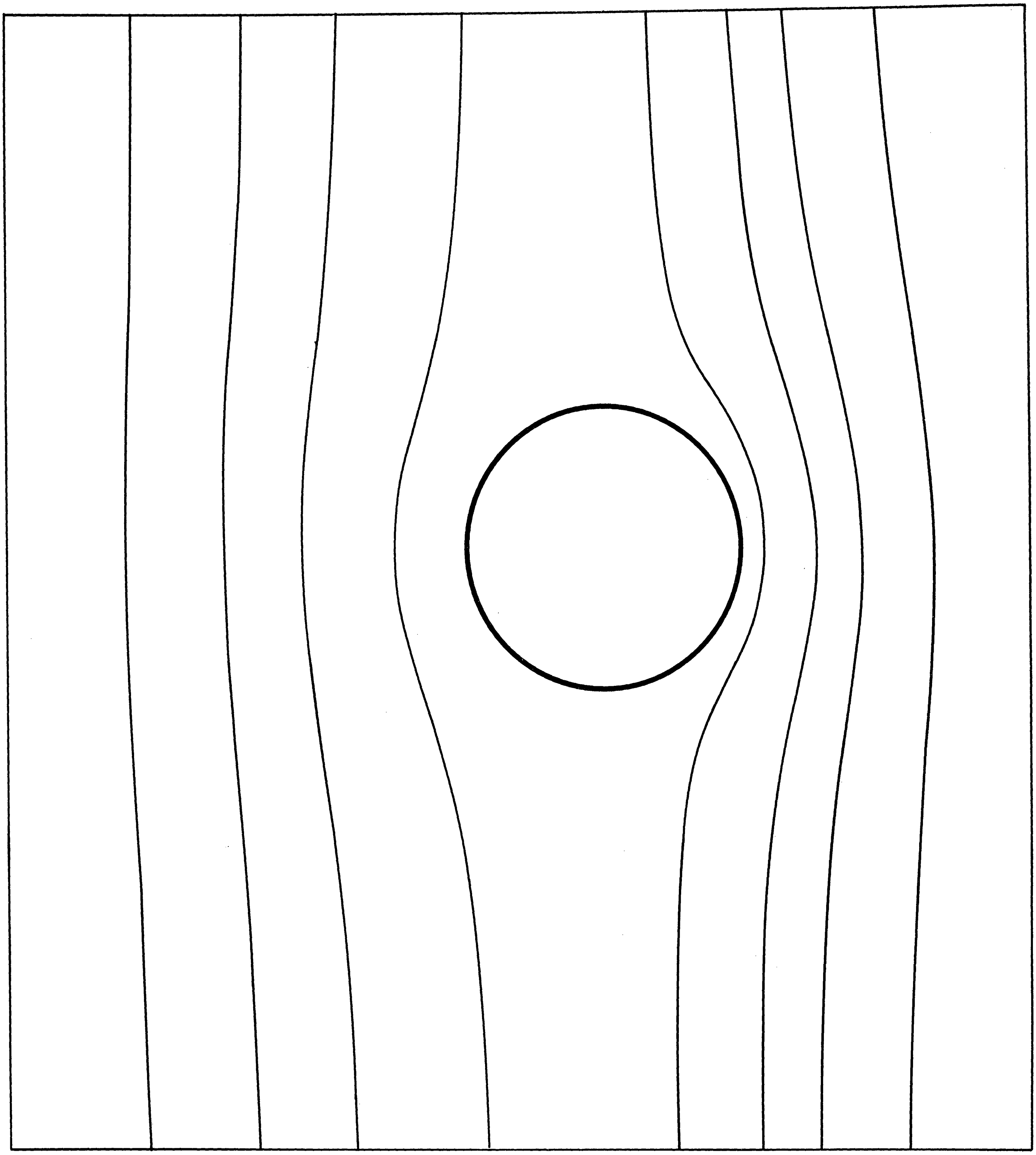


Fig. 12

Streamlines Around a Cylinder as Determined with Painted Panel

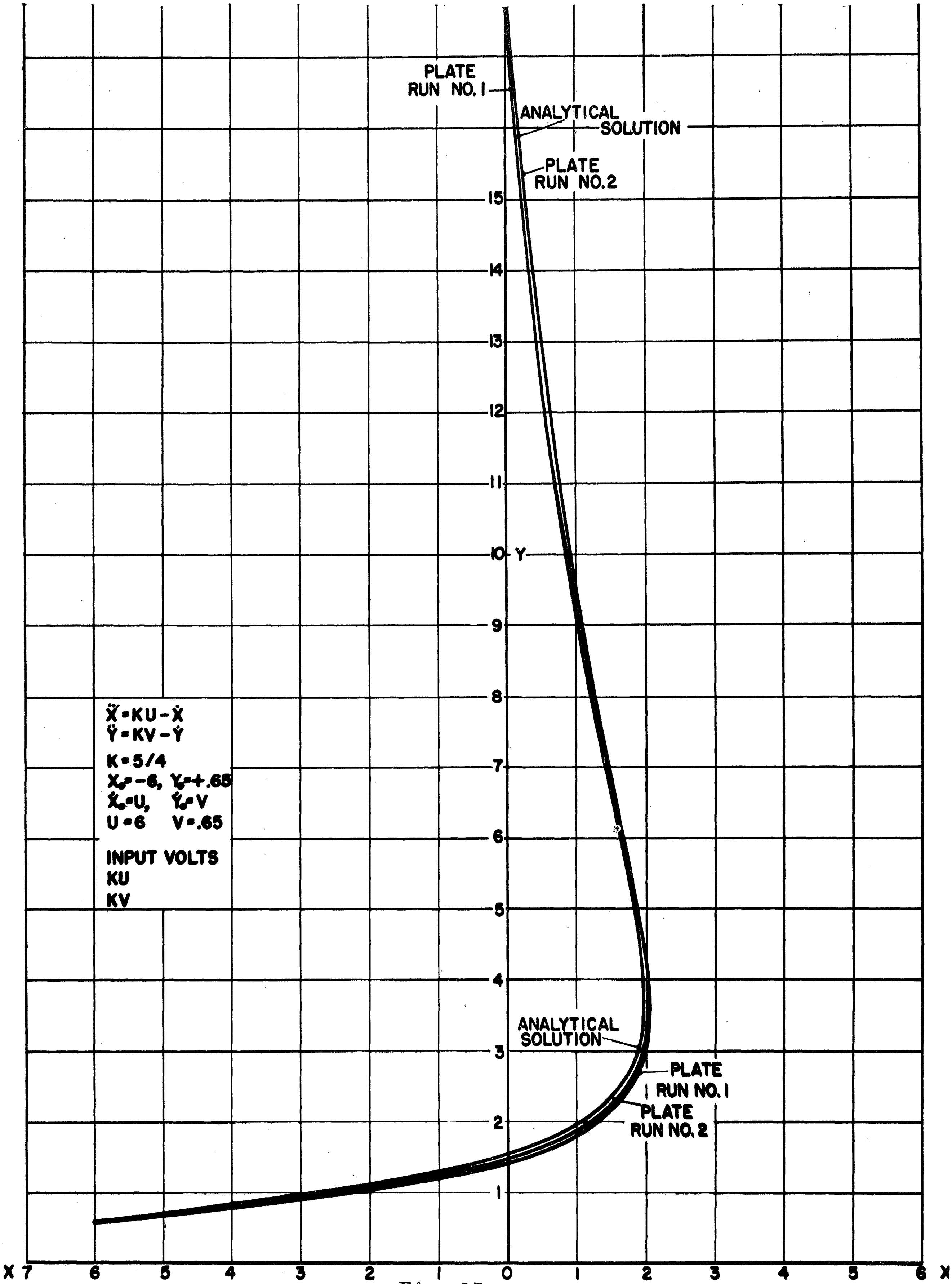


Fig. 13

Trajectory of a Drop Comparison of Analytical Solution
and
Solution Using Painted Panel

LITERATURE REFERENCES

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