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A pulsating-fluidised bed system for the electrolytic coating of diamond particles

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A PULSATING-FLUIDISED BED SYSTEM FOR THE ELECTROLYTIC COATING OF DIAMOND PARTICLES

A thesis presented to the Department of Chemical Engineering in the Faculty of Engineering of the University of the Witwatersrand in fulfilment of the requirements for the Degree of Master of Science in Engineering

by

BRUCE IAN DEWAR

I declare that this thesis is my own work and has

not been submitted previously for a degree at

any university.

Ekwan

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A B S T R A C T

The thesis concerns the development of a pulsating-fluidised bed system for the electrolytic copper coating of diamond particles of approximately 326 μ. This system shows a number of advantages over the conventional rotating barrel method. The most noteworthy are:-

1. Agglomeration of the particles is effectively eliminated.
2. Adherence of the particles to the current feeder is minimised.
3. Higher current densities can be used.
4. Smaller batches of diamonds can be handled if required.
5. Increased density of the copper coat is obtained.
6. Degree of roughness of the copper coat can be more effectively controlled.
7. A cathode efficiency of 93% was obtained which was essentially independent of operating conditions.

1.0. INTRODUCTION

Diamond has made a major contribution to modern economy by making possible a unique engineering tool that can easily cut and shape hard materials with precision. The uniqueness of this tool arises from the fact that diamond is the hardest substance known to man.

The parts played by diamond in modern mass production techniques are many and varied, ranging from abrasive polishing pastes to wire-drawing, to use in saws and in grinding wheels. Grinding wheel grits account for approximately 37% of the total industrial diamond utilization in the world today. Industrial diamond abrasives are comprised of both natural and synthetic diamond. With the advent of synthetic diamond, particles can be produced with varying properties according to usage.

Grinding wheels are manufactured which contain diamonds set in either a metal or a resin matrix depending on the type of diamond and the material to be ground. As far as resin bond grinding is concerned the most far reaching development in recent years has been the introduction of metal clad diamonds for these grinding wheels. The metal coat serves three important purposes:

1. Metal adheres to resin much better than diamond does hence the keying of the particle in this bond is improved.
2. Wheel life is prolonged because the metal coat retains the fractured particles of diamond.
3. Premature charring of the resin bond is eliminated as the metal acts as a heat sink.

Metal coating of diamond therefore is an important aspect of diamond technology and as grinding enters new fields this aspect

is likely to become even more important in the future.

The two major mechods of metal coating diamond at present are the electroless chemical deposition of metal from the liquid phase and the electrolytic deposition of metal. The second method requires as starting material diamond particles which already have a layer of metal deposited on them. This layer is usually prepared by the electroless method. The electrolytic coat is considered to be more effective than the electroless coat because it is a rougher coat and its keying with the resin is therefore superior.

Handling diamonds during the electroless coating operation presents no problems but during electrolytic coating numerous difficulties arise. The aim of this study was to find a problem-free system for handling diamond particles during electrolytic plating operations.

2.0. THE ORIGINAL SYSTEM AND ITS PROBLEMS

Until now, the electrolytic plating of the diamond particles was carried out in a barrel system. The barrel was made of an inert material and two metal rings were s t through the wall of the barrel. These rings were next to, but insulated from, each other and they transferred the necessary current to the inside of the barrel. One of these rings, the current feeder,* was divided into three sections and the design of the electrical circuit enabled these sections to be alternately positively and negatively charged. The second ring

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* The term "current feeder" is used in place of "cathode" as the cathode for a particulate plating system is the total surface area of all the particles in contact with the negative electrode.

conveyed the anodic current to the anode which was a metal rod fitted along the axis of the barrel. The diamonds to be electrolytically coated (i.e. those which already had an electroless metal coat on them) were poured into the barrel which was then filled with the electrolytic plating solution. The barrel was then rotated on rollers. Brushes situated in convenient positions carried the necessary current to the two metal rings set through the barrel wall. On rotation of the barrel the diamonds rolled to the bottom where they were negatively charged on contact g the current feeder, positive metal ions were reduced onto these particles and in this way electrolytic plating took place.

The first problem encountered with this system was the coherence of the diamonds being plated to form clusters. This phenomenon is termed agglomeration.

Adherence to the current feeder presented the second major problem of this system. The current feeder on rotating free of the diamonds became positively charged. This change in polarity was necessitated by the fact that diamonds adhered to the current feeder and the positive charge forced most of these particles to break away from the electrode.

To prevent excess agglomeration and adherence low current densities** had to be used which resulted in low plating rates. Also it was found that batches below 50 gm of diamond grit were almost impossible to coat. Between 50 gm and 600 gm proved to be the most workable sizes but it was found that barrels of varying dimensions had to be used to accommodate this range.

It was postulated that agglomeration and adherence took place because the hydrodynamics of the system allowed the particles to

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** See Appendix I.

reside adjacent to one another, or in contact with the current feeder for too long. Therefore in order to overcome these two major problems a system had to be developed which would reduce this time, i.e. increase the movement of the particles with respect to each other and to the current feeder.

3.0. ELECTROCHEMICAL PRINCIPLES

Electroplating is the process of depositing a metal coat by means of electrolysis and therefore the development of any new system would have to be approached with the principles of electrochemistry as a foundation.

Generally the electrochemical operation is a combination of two kinds of processes; firstly the motion of the ions from the bulk of the solution to an electrode, and secondly the discharge, or the reaction of these ions in contact with the electrode.

The first process is achieved through diffusion which causes the ions to move from the unchanged bulk of the solution to the impoverished region at the cathode.[1] According to Fick's Law, the rate of diffusion of a constituent A in a mixture is proportional to its concentration gradient.

$$N_A = -D_A \frac{\partial C_A}{\partial y}$$

N_A is the molar rate of diffusion of constituent A per unit area.

C_A is the molar concentration of constituent A.

D_A is the diffusivity of A.

The second process is the electrical migration of cations and is superimposed on the diffusion process.

$$N_A = -D_A \frac{\partial C_A}{\partial y} - C_A W_A Z_A \frac{\partial V}{\partial y}$$

W_A is the mobility of the ion of species A.

Z_A is the valence of the ion of species A.

$\frac{\partial V}{\partial y}$ is the electrical potential gradient.

Normally diffusion is more important than migration.[2] Thus in most cases the kinetics of the electrochemical processes are limited by diffusion and under these conditions concentration polarization is said to occur.

The case in question entails the deposition of copper (II) (Cu++) ions from an electrolyte of sulphate ions, as a copper-sulphate plating bath (see Section 5.4.1. for formula) was used in the experiments. Thus we are considering the particular case of the discharge at the cathode of the cation of a salt in low concentration in a supporting electrolyte with a common anion, the concentration gradients of all the ions at any point in the boundary layer are therefore proportional to each other.

The electrical neutrality equation

$$\Sigma C_A Z_A = 0$$

is valid at any point in the solution except at the electrodes.

Thus the measured current depends only on the concentration gradient of the ion that discharges (copper II) and the electroplating process occurs as if the gradient of electrical potential does not interfere.

$$\therefore \quad N_A = - D_E \frac{\partial C_A}{\partial y}$$

D_E is the effective diffusivity.

Usually the concentration gradient in the diffusion boundary layer can be considered to be constant.

$$\therefore \quad N_A = - D_E \frac{C_B - C_e}{\delta}$$

C_B is the concentration of the ion in the bulk of the solution.

C_e is the concentration of the ion in contact with the electrode.

δ is the thickness of the diffusion layer.

This thickness, δ, is related to δ_o the thickness of the hydrodynamic boundary layer by the following relationship:

$$\delta = \delta_o / (S_c)^{1/3}$$

S_c is the Schmidt Number and is of the order of 1,000 for liquids.

Although δ is ten times smaller than δ_o, they are proportional for any given state of agitation of the liquid phase. As the turbulance increases δ_o and hence δ decrease following well known laws of fluid mechanics.[3]

This decrease in δ causes the molar rate of diffusion of constituent A (N_A) per unit area to increase.

The system developed must therefore provide conditions necessary for increasing N_A. This means that the particles must be kept in constant motion in order to decrease the value of δ. This turbulance would be caused by rapid fluid flow which would keep C_B homogeneously constant. The constant motion of the particles would cause the hydrodynamic boundary layer to be constantly renewed and thus ion

depletion in this layer would be considerably reduced. Current densities greater than previously attainable would then be possible.

4.0. LIFT-PUMP SYSTEM

In attempting to overcome the problems outlined in section 2.0, a lift-pump system was initially envisaged (Figure 1), based on the electrochemistry discussed in section 3.0. The electrolytic plating solution was circulated through the cell by a pump. The cell itself had a venturi tube suspended in it just above the solution inlet. Situated approximately one centimetre or so directly above the venturi tube was the current feeder. Numerous positions, shapes (the most successful being the one shown in Figure 1) and sizes of current feeder were tried. The anode was a copper tube encircling the venturi tube. The flowing electrolyte drew the particles up through the vortex of the venturi tube. These particles then struck the current feeder and were drawn down on the outside of the venturi tube to the bottom of the cell where they were again pulled up into the venturi tube by the flowing solution. Thus particles could not adhere to the current feeder as they were drawn away from the latter after striking it. Agglomeration could not occur because when particles resided next to one another for any length of time (i.e. at the bottom of the cell) they were not being cathodically charged. This system provided the necessary turbulent flow to satisfy the electrochemical requirements.

However, this system presented a new problem in that the particles had to strike the current feeder in rapid succession to prevent the latter from becoming coated with a rough layer of copper. When this coat was allowed to form, particle motion was disrupted. When

FIG. 1

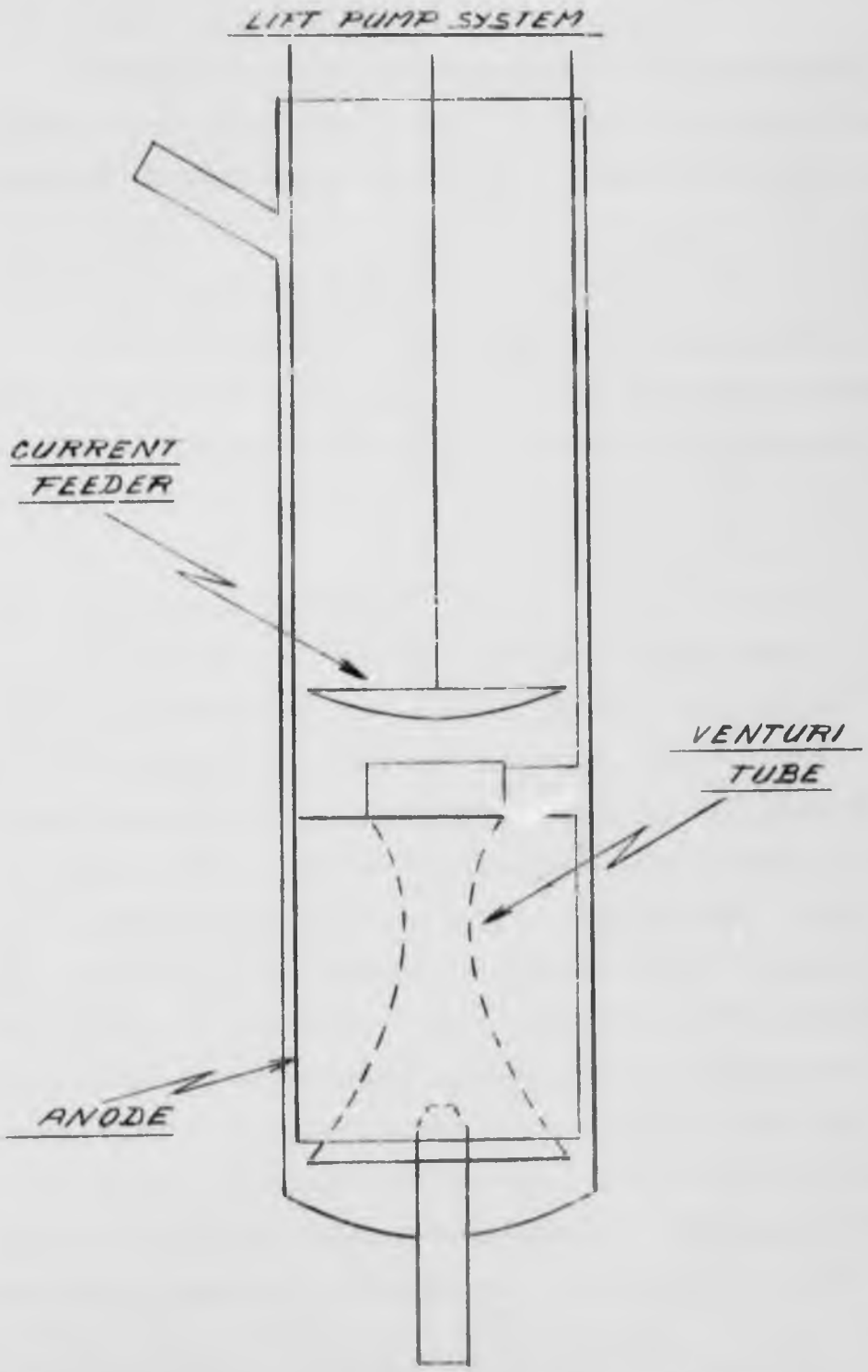
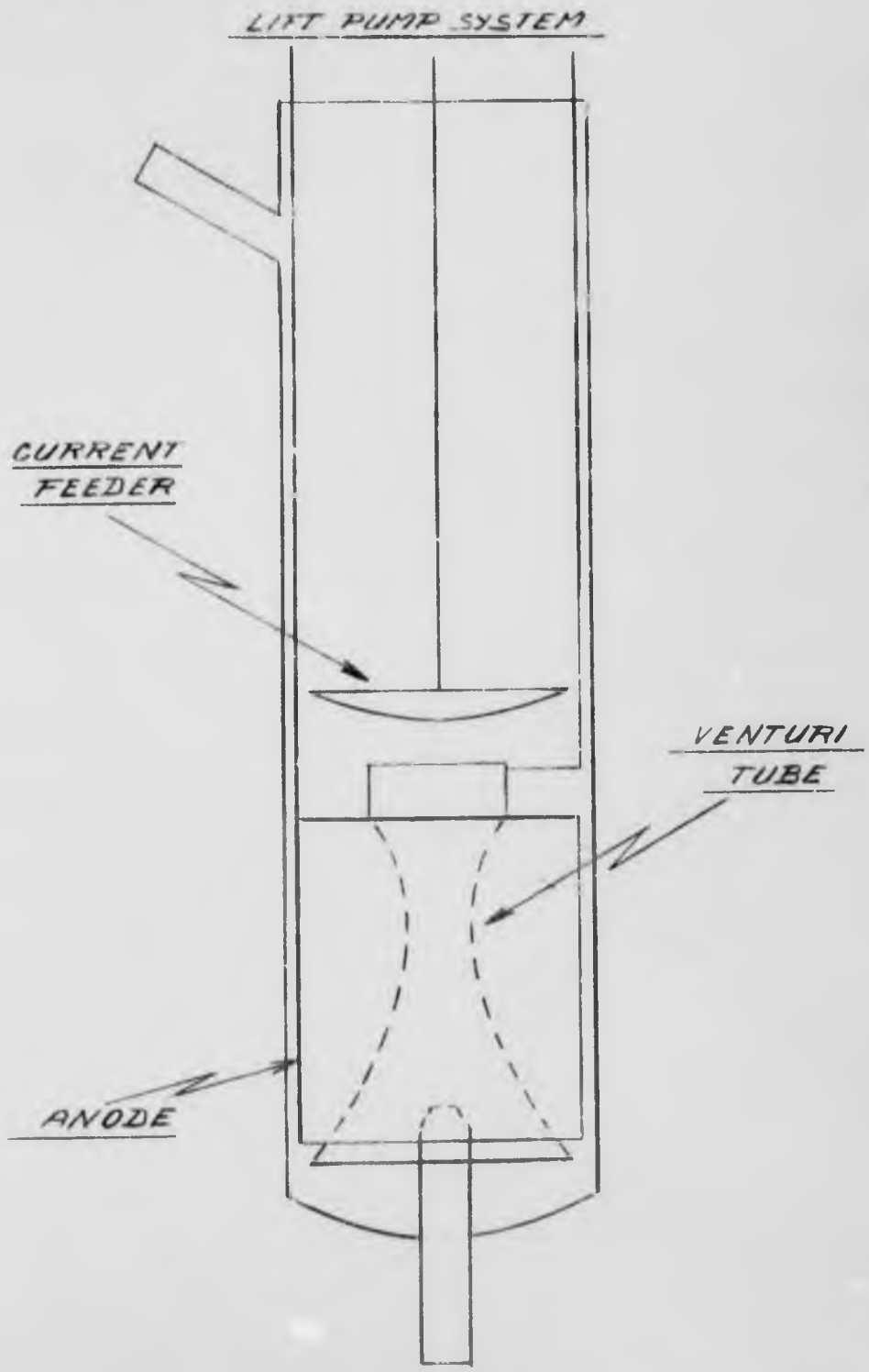


FIG. 1



the diamond particles were circulating at velocities sufficient to prevent the formation of this coat on the current feeder, the particles struck the latter with such force that the initial electroless metal coat on the diamond was chipped. Using thicker electroless coats met with limited success.

Although the lift-pump apparatus eliminated the major hydrodynamic problems of the barrel system (see section 2.0), it was abandoned because of the above problem and the very low plating rates observed.

5.0. THE FLUIDISED BED SYSTEM

The failure of the lift-pump system led to experimentation with a fluidised bed. The design and operating procedure was modified considerably during the course of the study with an aim to improving its performance.

5.1. Hydrodynamic Considerations

The phenomenon of fluidisation involves a certain mode of contacting granular solids with fluids. The fluid can either be a gas or a liquid. In the present study it is a liquid. Here a bed of solid particles is supported on a rigid permeable material in a vertical tube. The liquid is then forced upwards through the porous material into and through the bed. When the weight of this bed of particles is just supported by this flow, the bed is said to be incipiently fluidised. In this condition the individual particles become somewhat disengaged from each other and readily move around the bed. A further increase in liquid flow will cause the bed to expand to accommodate this increase. A bed which has passed the point of incipient fluidisation is known as "a dense-phase fluidised bed" or simply as a "fluidised bed". The solid particles in

this fluidised bed move about at random and provided the bed is not too wide or too deep[4] the mixing of the particles is very good. The constant motion of the particles enables the hydrodynamic boundary layer to be continually renewed.

The fluidised bed has many of the properties of a liquid, for example on tilting the containing apparatus, the upper surface of the bed remains horizontal.

The term "particulate fluidisation" as opposed to "aggregative fluidisation" is used to describe a liquid-fluidised bed in which the point of incipient fluidisation has been passed. The latter term is used for gas-fluidised beds in which some of the gas passes through the bed as bubbles. As the gas flow rate increases above the incipient flow rate bubbles grow and appear more frequently, until their frontal diameters are equal to the diameter of the containing apparatus. Under these conditions the bed is said to be slugging. No bubbles are formed during particulate fluidisation, the liquid passing smoothly through the interstices

5.2. The Size of the Cell

As the difficulties encountered with the barrel system were most severe when small batches of diamond were coated, it was decided to develop this system primarily to handle these small batches. The grit chosen to be coated was a 45/50 mesh (U.S. sieve series i.e. ± 326 μ) Saw-Diamond Abrasive (SDA).

From work done by Shuster and Kisliak[7] it is evident that for the same bed expansion ratios and values of L/D_t (L is the bed height cm, D_t is the internal diameter of the tube cm) the large diameter beds exhibit a poorer performance than the smaller diameter beds.

For this reason and the fact that batches of 18 gm of diamond were to be coated the cell diameter had to be reasonably small in order to give an acceptable L/D_t ratio.

However, the cell also had to house electrodes. The electrode assembly was chosen so as to present the least inhibiting influence on the hydrodynamics of the fluidised bed. The negative electrode (current feeder)* of the system chosen was a carbon rod suspended in the centre of the cell. This smooth rod appeared to have no effect on the performance of the fluidised bed. The anode was a copper tube suspended in the electrolyte above the fluidised bed. The dimensions finally chosen for the cell were internal diameter 1.90 cm and outside diameter of the current feeder 0.64 cm (see Figure 2, 3 and Plates 1 and 2).

5.2.1. Fluid Distributor

Work has been done by Grohse[5] in connection with the fluid distributor as it pertains to the gas fluidised system. The effects of the distributor are expected to be basically the same in either a gas or a liquid fluidised bed. A porous plate gave rise to a well defined point of incipient fluidisation and there was no tendency to channel. With a screen or a multi-orifice gas distributor the point of incipient fluidisation was not very clearly defined and channelling occurred. From these considerations and those in Section 5.2. it was decided that the cell should be a glass tube with a porous sintered disc for the fluid distributor.

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* See note on foot of page 3.

FIG. 2

CELL FOR THE PULSATING FLUIDISED BED SYSTEM

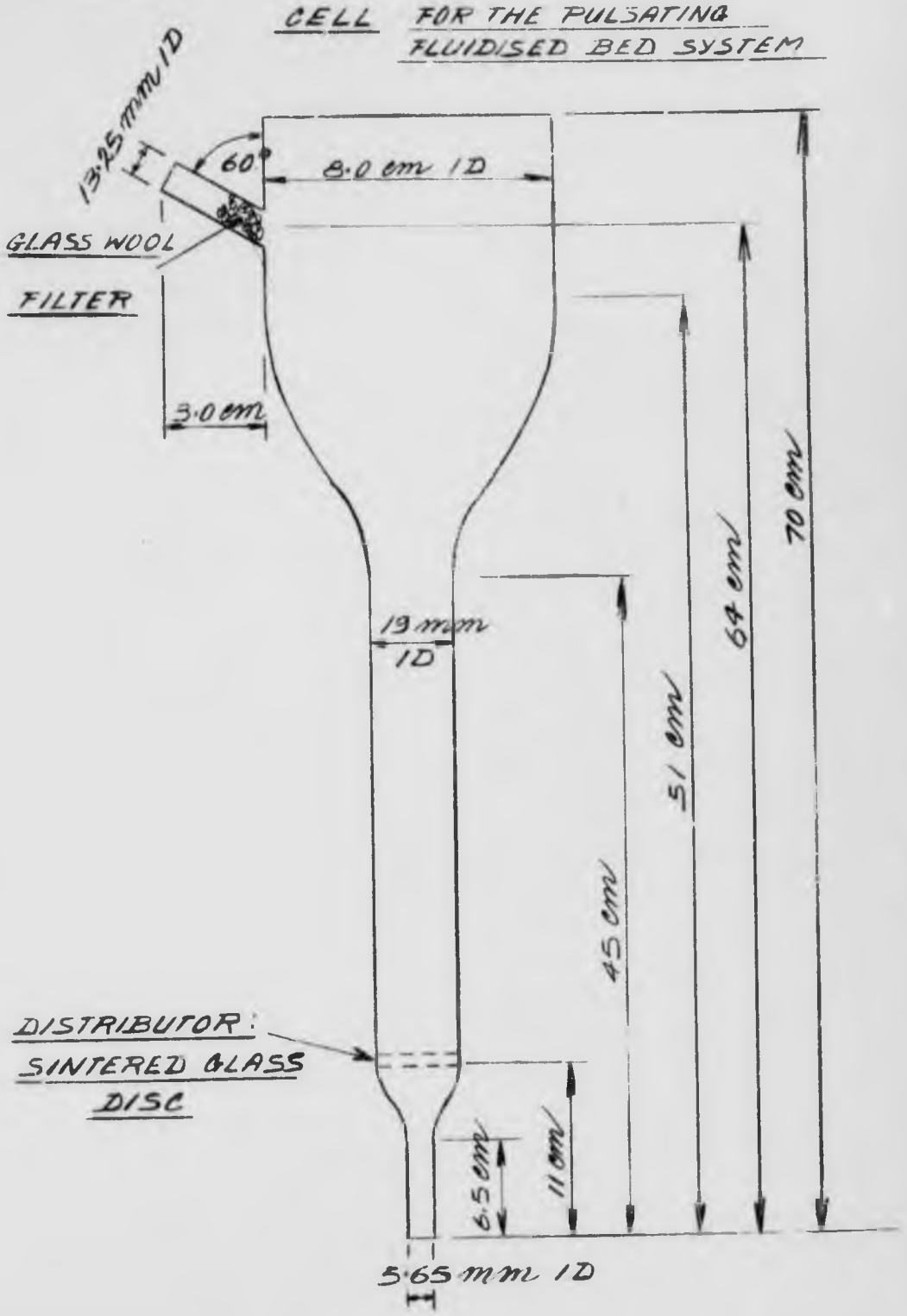
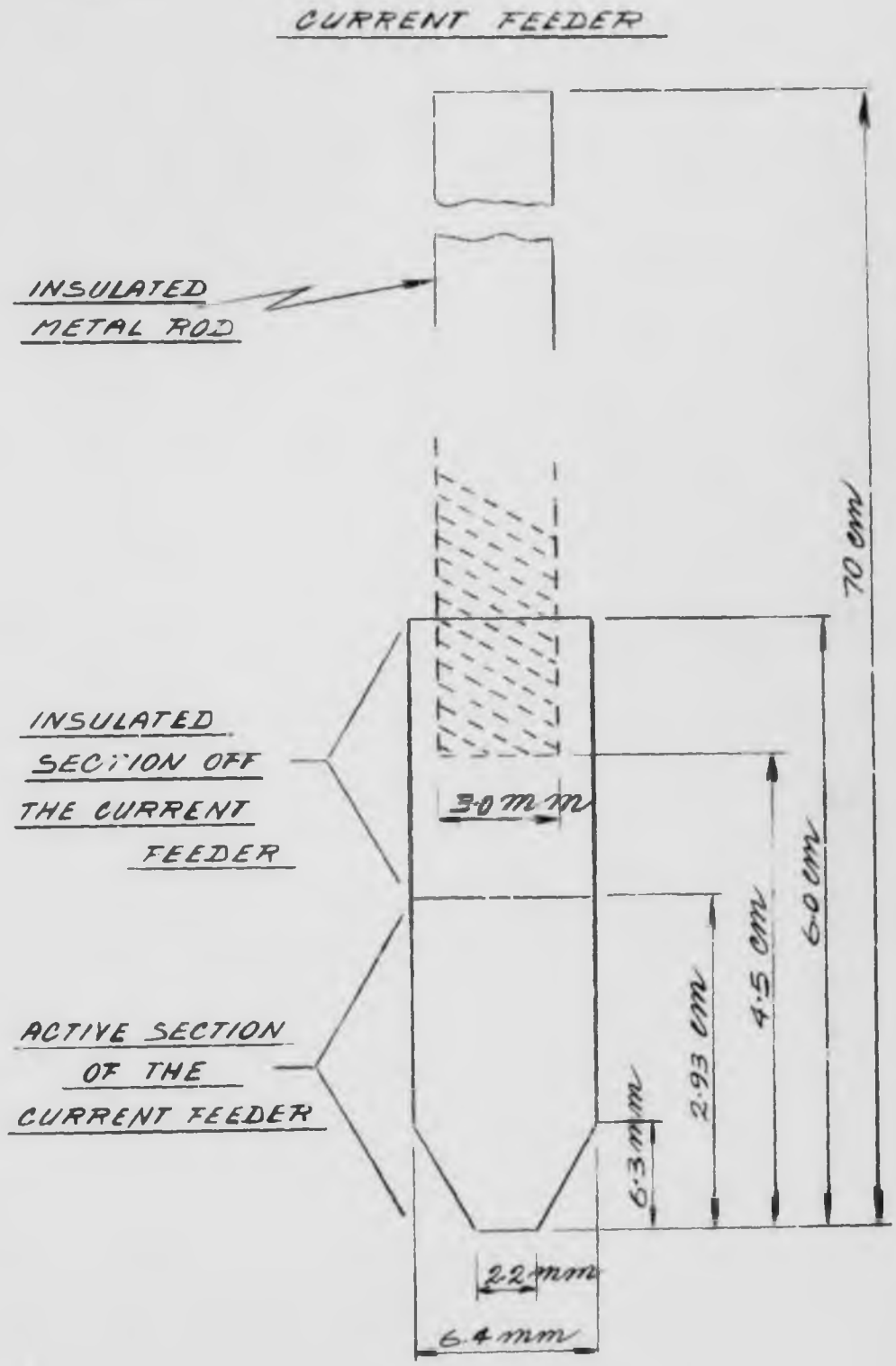
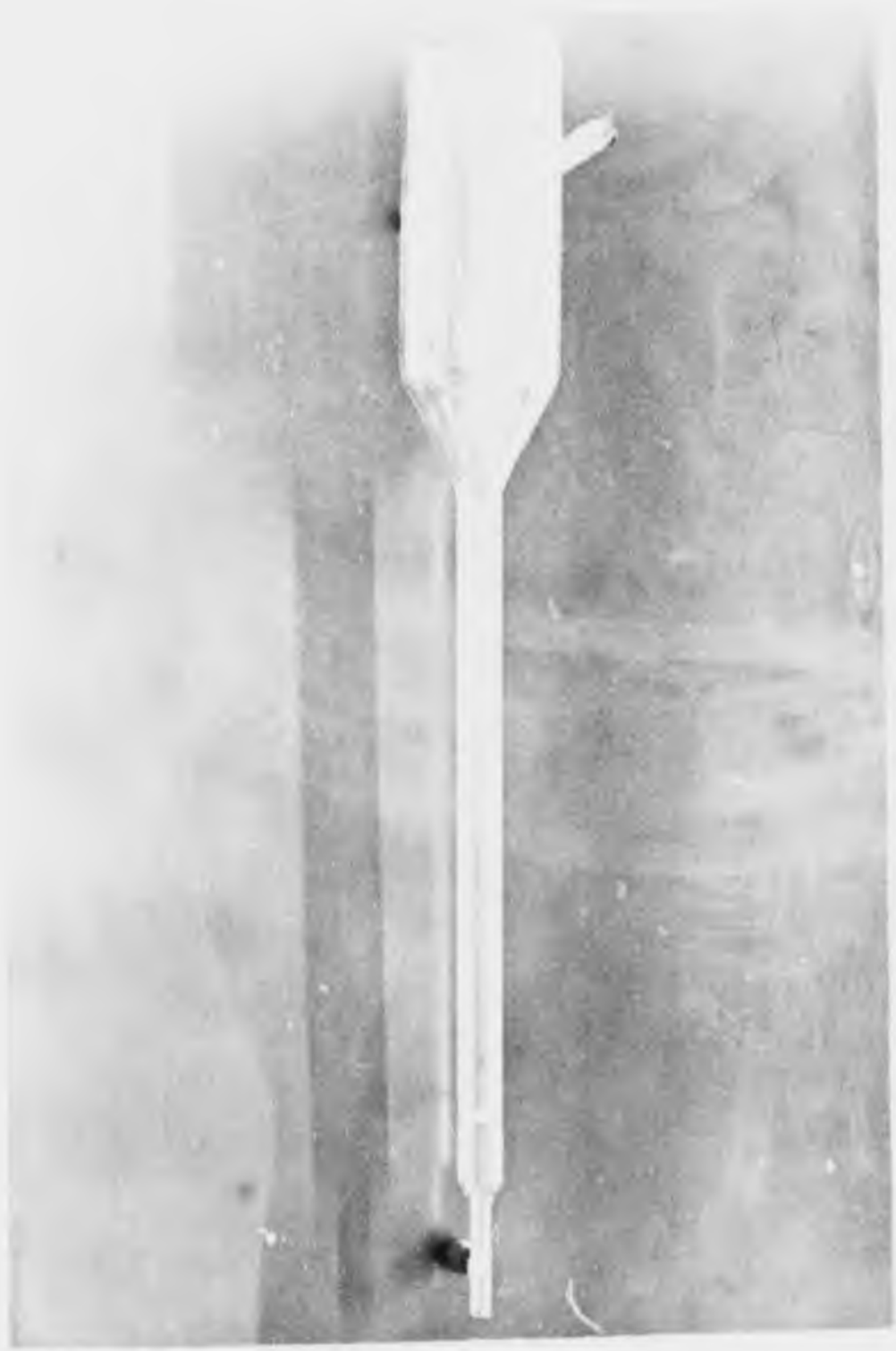


FIG. 3


CURRENT FEEDER
INSULATED METAL ROD
INSULATED SECTION OFF THE CURRENT FEEDER
ACTIVE SECTION OF THE CURRENT FEEDER
3.0 mm
6.3 mm
2.93 mm
5.4 mm
6.0 mm
7.0 mm
2.2 mm
6.4 mm



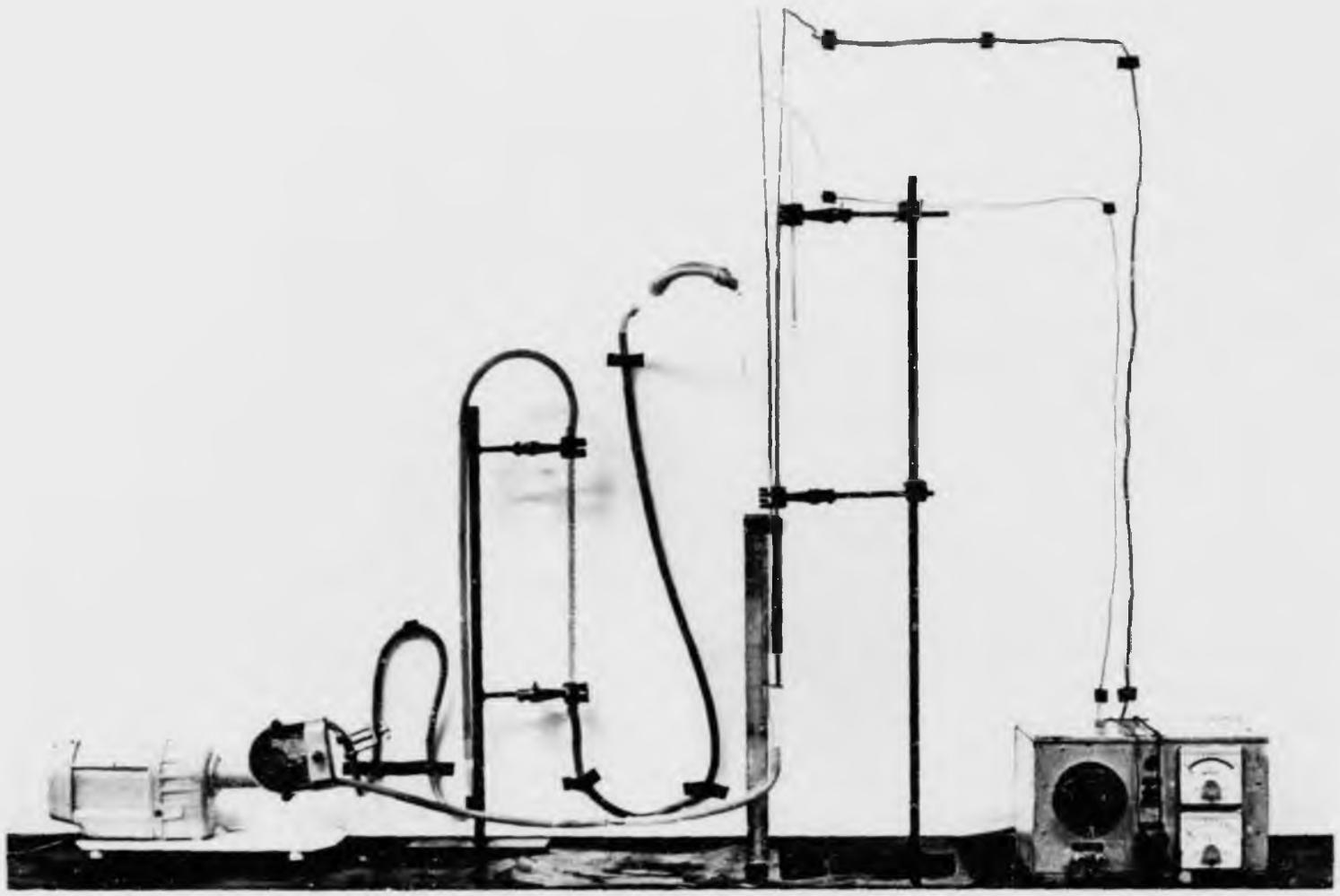


Plate 2: Pulsating-fluidised bed system.

5.3. Mechanics of Fluidisation

Extensive work has been done on the prediction of the incipient fluidisation velocity and pressure drop across the bed. However, the relations of the basic parameters are still semi-empirical. At incipient fluidisation the pressure drop is just sufficient to support the weight of the particles viz.:

$$\frac{\Delta P}{L} = (\rho_s - \rho)g\,(1 - \varepsilon o) \qquad \ldots\ldots\ldots\ldots\ldots \quad (1)$$

Kozeny[6] and Carman[7] originated a theory pertaining to the flow of fluid through a fixed bed of particles under the influence of a uniform pressure gradient.

By extending the theory of fluid flow through a parallel-sided passage they obtained the following equation for packed spheres:

$$\frac{\Delta P}{L} = \frac{C\mu\, U_o (1 - \varepsilon o)^2}{D^2\, \varepsilon o^3} \qquad \ldots\ldots\ldots\ldots\ldots \quad (2)$$

Choosing Carman's[8] predicted value of C = 180 and combining equations (1) and (2)

$$\frac{C\mu\, U_o (1 - \varepsilon o)^2}{D^2\, \varepsilon o^3} = (\rho_s - \rho)g\,(1 - \varepsilon o)$$

$$U_o = \frac{(\rho_s - \rho)g\, D^2\, \varepsilon o^3}{(1 - \varepsilon o)\, C\mu} \qquad \ldots\ldots\ldots\ldots\ldots \quad (3)$$

Lewis[9,11] adopted a similar procedure to arrive at the equation

$$\frac{\Delta P}{L} = \frac{C U_o (1 - \varepsilon o)^2}{D_p^2 g \varepsilon o^3} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

Leva[10] used the value of 200 for C as this gave the most conservative value for the pressure drop

D_p is the diameter of the "equivalent volume sphere".

Thus, for a sphere

$$D_p = 6V/Ap$$

However, particles with an arbirary shape (e.g. the diamond particles) with volume V have a larger surface area than do spheres of volume V. The diameter of this arbitrarily shaped particle is given by

$$D_p = \frac{6V}{A\phi_s} = \frac{6V}{A_p}$$

A is the surface area of the arbitrarily shaped particle.

A_p is the surface of the "equivalent volume sphere".

ϕ_s is the shape factor and is a dimensionless quantity.

By replacing D_p by $D_p\phi_s$ Leva extends equation (4) to cover flow through beds of particles of arbitrary shape.

$$\frac{\Delta P}{L} = \frac{200\ U_o\ \mu\ (1 - \varepsilon o)^2}{D_p^2\ \phi_s^2\ g\ \varepsilon o^3} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

Combining equations (1) and (5)

$$\frac{200\ U_o\ \mu\ (1 - \varepsilon o)^2}{D_p^{\ 2}\ \phi_s^{\ 2}\ g\ \varepsilon o^3} = (\rho_s - \rho) g\ (1 - \varepsilon o)$$

$$U_o = \frac{(\rho_s - \rho) g^2\ D_p^{\ 2}\ \phi_s^{\ 2}\ \varepsilon o^3}{200\ (1 - \varepsilon o)\mu} \quad \ldots\ldots\ldots\ldots \quad (6)$$

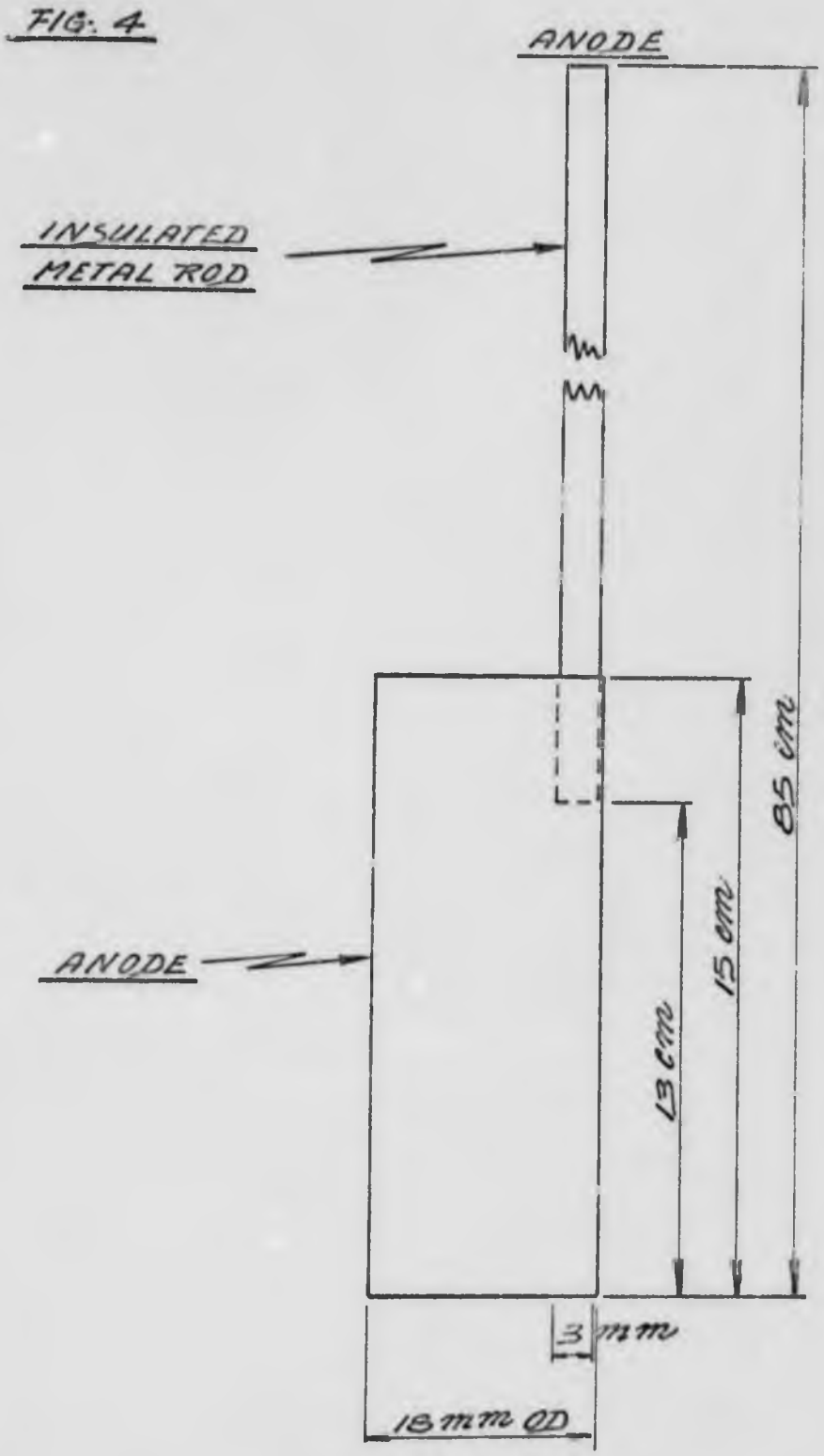
5.4. The Electrodes

As stated in section 5.2. the electrode assembly was chosen so as to present the least inhibiting influence on the hydrodynamics of the system. The electrodes used are described fully below.

The current feeder was a carbon rod (see Figure 3) connected to an insulated metal rod. By means of this insulated rod the current feeder was suspended along the axis of the cell. The tip of the current feeder rested in the centre of the sintered glass disc (see Plate 2). The insulated metal rod carried the current from the rectifier to the current feeder. The same electrode was used for all the experiments. Before it could be used its volume had to be determined as will be seen in Section 6.1. During each run a small amount of copper was plated onto the current feeder and in order to keep the dimensions of the latter constant this copper had to be removed. This was easily done by dipping the current feeder into a dilute solution of nitric acid. If the current feeder had been made of metal this would not have been possible and for this reason carbon was used.

The anodes were made out of copper sheet approximately 1 cm thick. This sheet was rolled into a tube 1.8 cm O/D and 18 cm long (see Figure 4). The anode was suspended by an insulated metal rod as shown in Plate 2. At all times the anode was kept at a distance of between 0.2 and 1.2 cm above the average maximum bed height (Section

FIG. 4



6.1.). The insulated metal rod carried the current from the rectifier to the electrode.

From an electrochemical point of view the electrode geometry of the cell had its short-comings. In the cell as it was used, the electric field flux was greatest at the top of the cathode decreasing downwards (see Figure 5).

5.4.1. The Electrolyte Solution

The electrolytic plating bath used is a well known acid copper plating solution of the following composition:

Copper Sulphate, $CuSO_4.5H_2O$	200 gm/l.
Sulphuric Acid, H_2SO_4	50 gm/l.
Specific Gravity, at 25°C	1.165
Gelatin	0.2 gm/l.

Two litres of this solution were required to fill the system. A fresh solution was made up every second run. During the course of two runs, neither the copper content nor the free acid content of the solution was depleted to any appreciable extent.

5.4.2. Electrical Supply

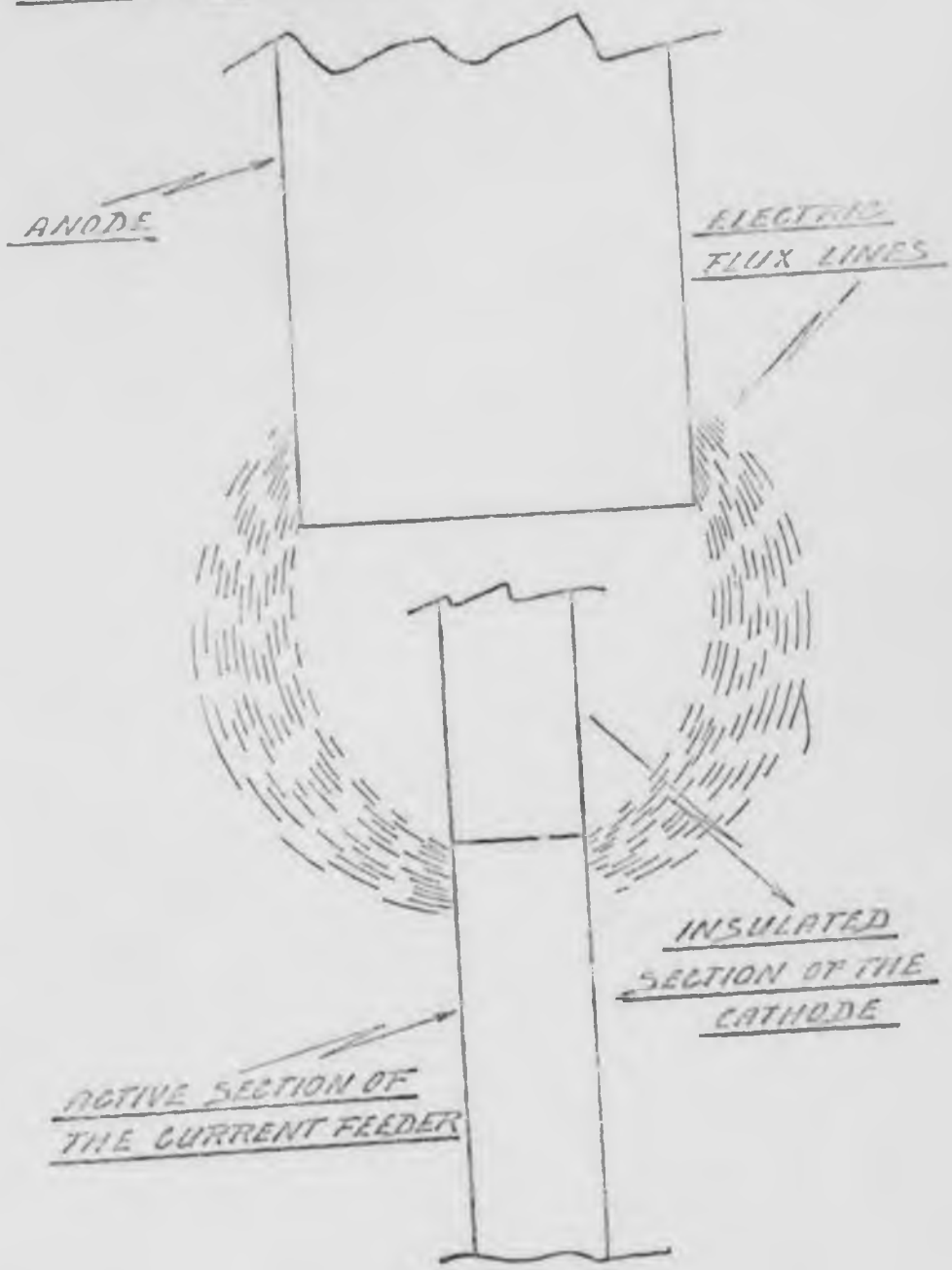
The electrical power supply was taken directly from a rectifier, having a maximum output of 10A at 20V. This rectifier was capable of continuous operation within its range of current and potential.

5.5. Calculated and Measured Incipient Fluid Velocity

The particles used had an average diameter of 326 μ and a density of 3.592 gm/cm^3 when coated with a thin electroless metal coat. The measured viscosity and density of the electrolytic plating

FIG. 5

FLUX OF THE ELECTRIC FIELD IN THE CELL



solution were 1.06, 10^{-2} gm/cm sec. and 1.08 gm/cm^3 respectively.

Equation (3) is

$$U_o = \frac{(\rho_s - \rho)g\ D^2\ \varepsilon o^3}{(1 - \varepsilon_o)\ C\mu}$$

and inserting the constants

C = 180

μ = 1.06, 10^{-2} gm/cm sec.

ρ = 1.08 gm/cm^3

D = 3.26. 10^{-2} cm

g = 981 gm/cm sec^2

ρ_s = 3.592 gm/cm^3

εo = 0.58 (measured by the method given in Ref. [10]).

We obtain

$$U_o = 0.637 \text{ cm/sec.}$$

However, when Leva's modified equation (6) is used

$$U_o = \frac{(\rho_s - \rho)g^2\ D_p^2\ \phi_s^2\ \varepsilon o^3}{C\ (1 - \varepsilon o)\mu}$$

C = 200 (See Section 5.3)

D_p = 1.177. 10^{-2} cm

$_s$ = 0.12 (estimated).

The reamining values being the same as those given above.

We obtain

$$U_o = 0.888 \text{ cm/sec.}$$

The measured incipient fluid velocity in the fluidised bed system was 0.12 l/min. For annular flow the average flow velocity is given by:

$$U_o = Q/\pi (r^2 - r_i^2)$$

Q is the volumetric flow rate, l/min.

r is the outer annular radius, cm

r_i is the inner annular radius, cm.

Q = 0.12 l/min.

$r = \frac{1.9}{2}$ cm (see Section 5.2 for the I/D of the cell)

$r_i = \frac{0.642}{2}$ cm (see Section 5.2 for the diameter of the cathode).

$$U_o = \frac{0.12.\ 10^3}{60\pi \left[(\frac{1.9}{2})^2 - (\frac{0.642}{2})^2\right]}$$

U_o = 0.796 cm/sec.

This is of the same order as the incipient fluidisation calculated from the equations developed by Leva and Carman.

However, even with the porous sintered disc, the point of incipient fluidisation in this system was not very well defined.

5.6. Pulsation of the Fluidised Bed

On putting the fluidised bed system into operation it was found that the problem of agglomeration had been eliminated. However, particles were still being plated onto the current feeder.

This problem was eliminated by causing the fluidised bed to pulsate. (see Fig. 7B) A peristaltic pump was used to circulate the electrolyte and thus to fluidise the packed bed. The rate of flow of the electrolyte was controlled by a throttle which was inserted in the flow system. The throttle was positioned on the inlet side of the pump, between the flowmeter and the peristaltic pump (see Plate 2 and Figure 6). This arrangement caused the pulsations to be transmitted to the fluidised bed via the flowing electrolyte. A frequency of 2.10 Hz for these pulses was chosen empirically, and was fixed for the duration of the experimental runs by setting the speed of rotation of the peristaltic pump. This pulsation frequency produced an amplitude in the fluidised bed height of 0.35 cm, equivalent to a volume fluctuation of 0.84 cm^3.

In the pulsating bed the point of incipient fluidisation was impossible to determine, the reason being that the packed bed expansion under these conditions, was due partly to the fluid flow and partly to the fluid pulsation.

The reservoir (see Figure 6) effectively damped these pulsations and so prevented them from influencing the flowmeter readings.

6.0. THE PULSATING-FLUIDISED BED SYSTEM

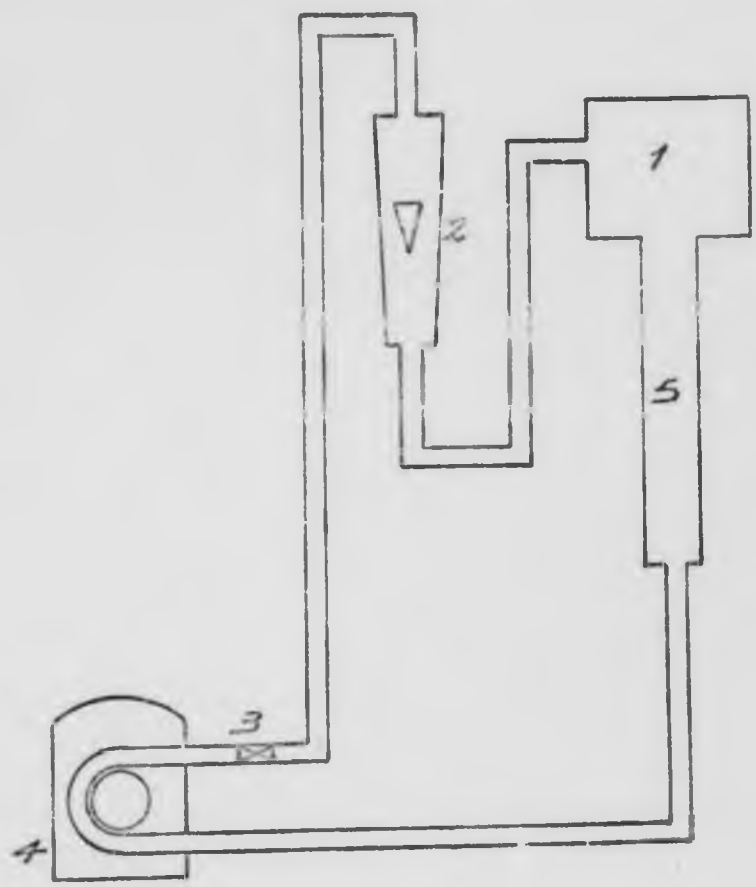
The following system was finally chosen because it eliminates the two major hydrodynamic problems referred to above.

The pulsating-fluidised bed cell is shown in Figure 2. It was constructed of glass tubing of various diameters, a sintered glass disc acting as a combined flow distributor and bed support.

A diagram of the electrolyte flow circuit is shown in Figure 6. The large top portion of the cell acted as a reservoir, without which the electrolytic solution would have become depleted of copper

FIG. 6

ELECTROLYTE CIRCULATION SYSTEM



1 ELECTROLYTE RESERVOIR

2 FLOWMETER

3 FLOW CONTROL THROTTLE

4 PERISTATIC PUMP

5 CELL

FIG. 7

NORMAL FLUIDISED BED

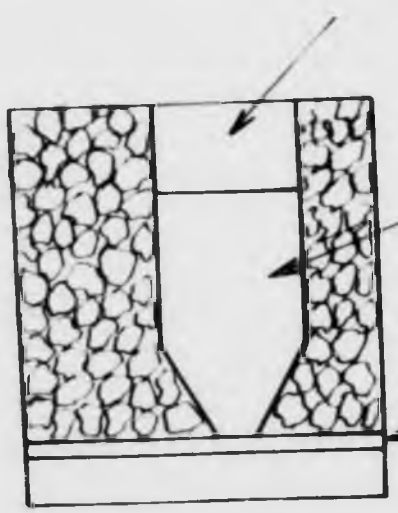
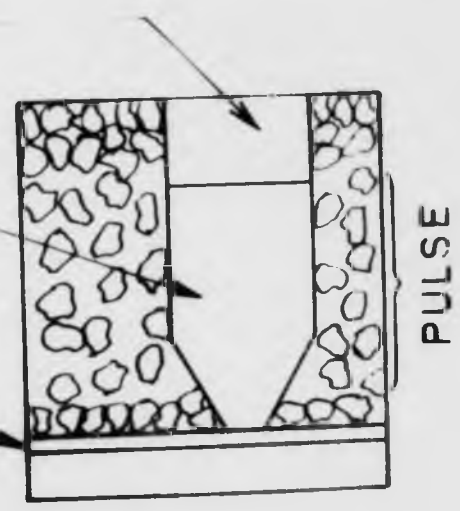


FIG. 8

PULSE PASSING THROUGH
THE FLUIDISED BED



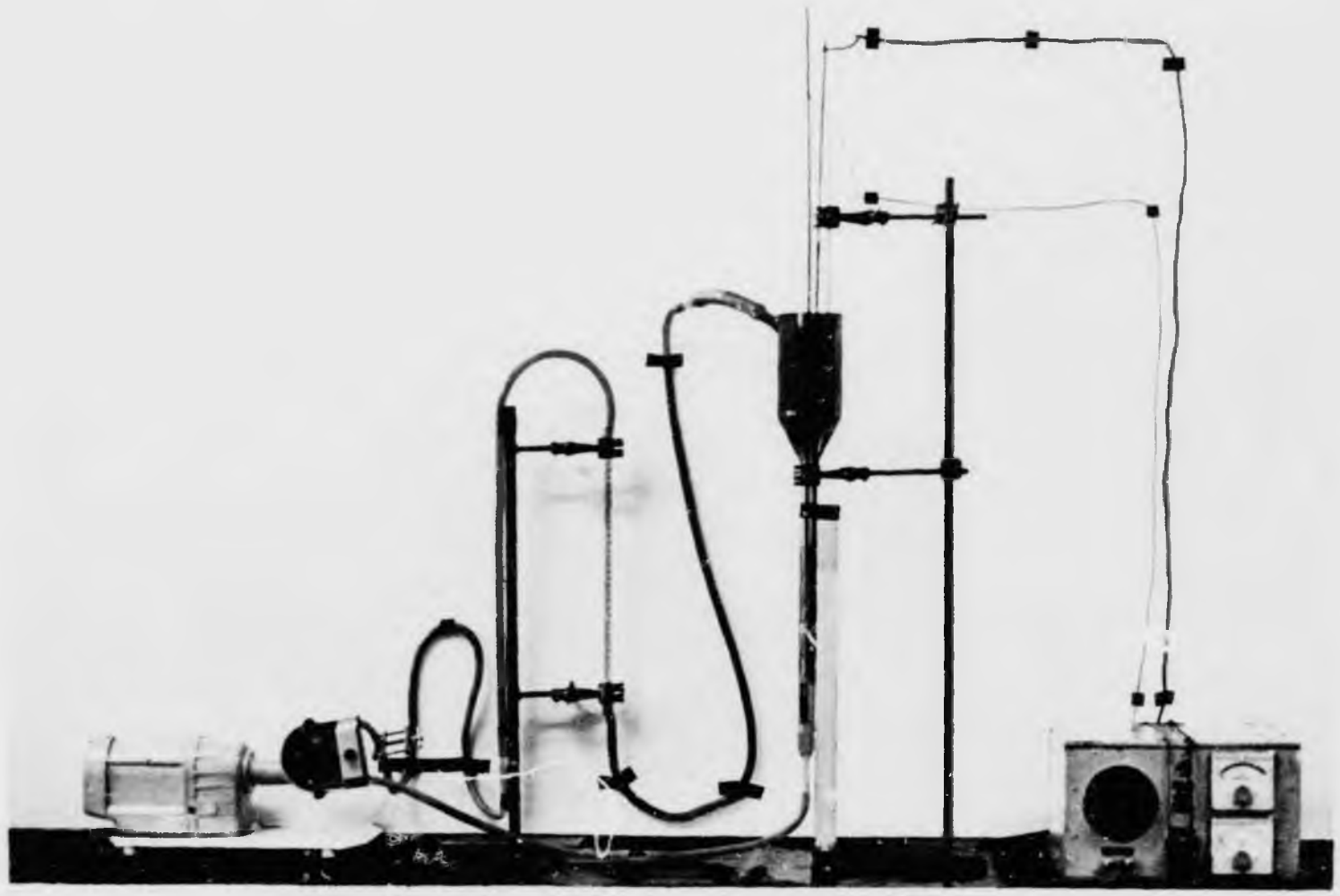


Plate 3: Pulsating-fluidised bed system loaded with Diamonds.

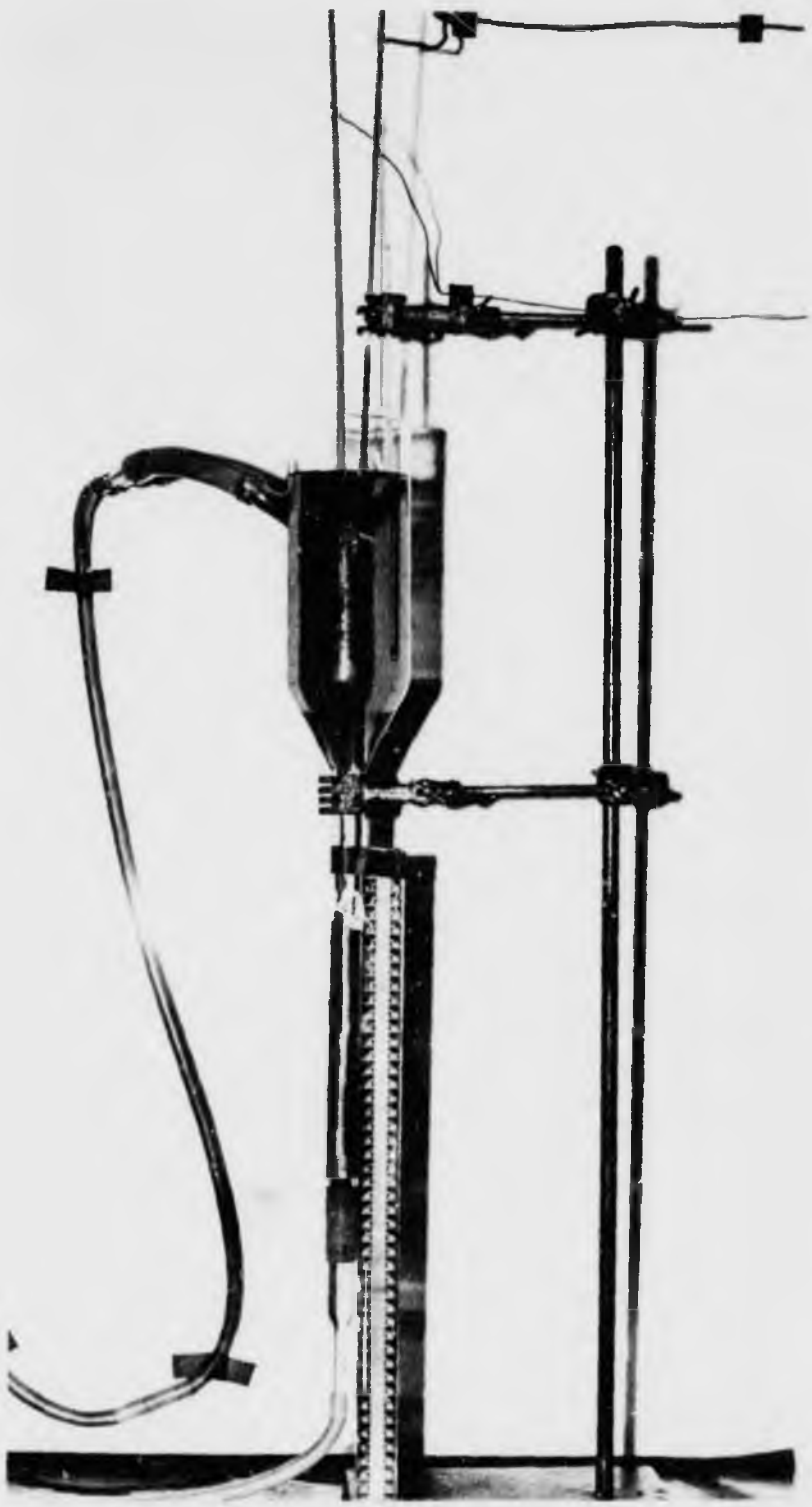


Plate 4: Operating System

too rapidly during an experimental run. A plug of glass wool was inserted in the mouth of the reservoir outlet. This glass wool plug acted as a filter, preventing metal flakes and other foreign bodies from fouling the system.

From the reservoir the solution was circulated through the system by a peristaltic pump. The flow to the cell was indicated by a rotameter with a Korannite float. The flow control was excercised manually by adjusting a throttle placed on the inlet side of the peristaltic pump. This position was selected for the throttle as it caused the required pulsations when so situated.

6.1. The Bed Expansion Tables

Tables relating the Static Bed Height (S.B.H.) of the grit in the cell and the volume occupied by this grit (Static Bed Volume (S.B.V.) with the Expanded Bed Height (E.B.H.) and its volume (Expanded Bed Volume (E.B V.), were drawn up for volume expansions of 5, 10, 15 and 20%. The object of these tables was to facilitate rapid conversion between S.B.H. and E.B.H. during experimental runs.

6.2. Range of Experimental Conditions

A charge of 18 gm of electroless coated grit was coated electrolytically during each experimental run. This 18 gm charge comprised 17 gm of diamond and 1 gm of nickel. The duration of the plating run was sufficient to enable approximately 17 gm of copper to be deposited. Thus the initial weight of the particles was almost doubled during a run.

The speed of rotation of the peristaltic pump was set at a constant value thus giving a constant pulsation frequency of 2.10

Hz. With this pulsation frequency the amplitude of the bed height pulsations varied between 0.27 and 0.40 cm, equivalent to an average volume fluctuation of 0.84 cm^3.

According to Lamb et al.[12] temperatures for this electrolytic plating bath may vary between 18 and 60°C with little effect on the rate of deposition. Thus the temperature was allowed to find its own level and this was found to vary between 22 and 45°C.

The current was kept constant at its pre-determined value and the mode position was adjusted so that it was kept at a distance of between 0.2 and 1.2 cm above the average maximum bed height. (See Section 6.5). Under these conditions the potential assumes the compensating value according to Ohm's Law.

Investigations were conducted at bed expansions of 5, 10, 15 and 20%, and currents of 1.5, 2.25 and 3.00A for each bed expansion. For each combination of these two variables two experimental runs were carried out. The bed expansions of 5 and 20% were virtually the limits of operation. Below 5% the bed surface was static and this allowed copper dendrites to grow on the surface which eventually would have short circuited the cell. For a normal liquid-fluidised bed in which the liquid flow rate is above the incipient flow rate, particulate fluidisation occurs. However, in this pulsating-fluidised bed the liquid flow rate required to exceed 20% bed expansion gave rise to aggregative fluidisation and slugging. This slugging caused the current to oscillate between wide limits thus rendering accurate current control impossible.

6.3. Operation

The apparatus was set up as shown in Figure 6 and Plate 1. The mirror scale was adjusted to read zero at the top of the sintered disc.

Approximately 30 gm of 45/50 mesh SDA grit had a 5% electroless nickel flash deposited on it. The particles thus had a complete nickel coat of approximately 1 to 2 μ thick. From this coated grit a sample of 18.000 ± 0.003 gm was weighed out. The 18 gm sample was rinsed in a 100 ml aliquote of 5% hydrochloric acid solution, in order to remove any oxide layer. On the appearance of the first bubbles the acid solution was poured off and the grit washed well with distilled water.

The grit sample was then washed into the cell with some of the electrolytic plating solution. The electrodes were inserted and connected to the electrical circuit. Electrolyte solution was then added to the cell until the cell outlet was covered. (Plate 3). The speed of rotation of the peristaltic pump was set and the throttle was closed.

The peristaltic pump was switched on. The throttle was opened to allow a flow rate of approximately 0.120 l/min. With these settings the cell was allowed to run for 3 minutes. (Plate 4).

6.4. Static Bed Height and Volume

After three minutes the pump was switched off. The average bed height was read off the mirror scale and recorded. The pump was then switched on for a few seconds, stopped again and another average bed height recorded. Three readings were taken in this way. The average of these three readings was called the Static Bed Height (S.B.H.). From the Bed Expansion Tables described in Section 6.1, the appropriate Static Bed Volume (S.B.V.) was recorded.

6.5. Expanded Bed Height and Volume

After recording the S.B.V., the pump was again switched on. The average minimum and average maximum heights of the pulsating fluidised bed were read off the mirror scale. The mean of these two bed heights was termed the Expanded Bed Height (E.B.H.). From the Bed Expansion Tables the Expanded Bed Volume (E.B.V.) was read and recorded.

The anode was then adjusted to between 0.2 and 1.2 cm above the average maximum bed height. At this point the temperature of the electrolytic solution was recorded. The temperature was measured at the bottom of the reservoir.

The current was then switched on and adjusted to the required value. If the required current could not be reached immediately (due to the limited output of the rectifier), it was taken up in a step-wise fashion until the required value was reached. Higher currents became possible after a time because as the copper was plated onto the particles, so the cell resistance decreased, thereby allowing the current to increase at a set potential.

6.6. Bed Height Adjustment

The required E.B.H. for the initial S.B.H. was read off the appropriate Bed Expansion Tables. The flow rate was then adjusted by means of the throttle in order to obtain a mean bed height (described in Section 6.5) equal to the required E.B.H.

As the anode was dissolved, so it had to be lowered in order to keep it between 0.20 and 1.2 cm above the average maximum bed height. The current rectifier was manually adjusted to keep the current constant at the pre-determined value.

6.7. Recordings and Adjustments

After the first ½ hour the temperature, flow rate, mean bed height, potential, current and time, were recorded. The current was switched off and the S.B.V. was determined as outlined in Section 6.4. The pump and current were then switched on again and if necessary the mean bed height was adjusted as outlined in Section 6.6 When this first set of readings had been taken, the necessary adjustments were made; the procedure was repeated every ½ hour. If a sample was to be taken before the end of this ½ hour period, then recordings and adjustments were made ½ hour before the sample was taken.

6.8. Sampling

A total of 4 samples were taken at convenient intervals during the course of each run. The samples were taken at the following times for runs conducted at the following currents:

Current (Amps)	Sample Time (Hours)			
	1st	2nd	3rd	4th
1.50	1.00	3.75	7.00	9.50
2.25	1.00	2.75	4.00	6.25
3.00	0.50	2.00	3.25	4.50

The procedure adopted was the same as that in Section 6.4, but once the S.B.V. had been obtained the pump was switched on agai. and a sampling tube was inserted into the centre of the fluidised bed. [This was a glass tube (5 mm O/D, 3 mm I/D, x 50 cm long)

attached to 40 cm (5 mm O/D) of silicone rubber tubing.] Solution and grit were pipetted into the rubber tubing and approximately 0.2 gm of grit was retained in the tube and the rest allowed to flow back into the cell. The grit in the sampling tube was then washed into a labled beaker and retained for a percentage coat determination which was carried out at a later stage. Once the sample was taken the S.B.V. was again determined. This did not usually alter significantly. If necessary the mean bed height was adjusted according to the procedure in Section 6.6. The switching-on procedure outlined in Section 6.7 was then followed.

On completion of the run the fourth sample was taken under the same conditions as the previous ones. The electrodes were removed from the cell. A small amount of copper had been plated onto the current feeder but this was removed by washing the current feeder in dilute nitric acid. The cell was disconnected from the circuit and the solution poured out and the coated grit was washed into a labled beaker. The sintered disc and the plug of glass wool were washed with dilute nitric acid and the cell was then ready to be used again. The sintered disc was always kept under solution in order to prevent it drying out.

The coated grit in the beaker was washed with distilled water, ethanol, and then dried on a hot plate. The grit was then screened in order to remove any copper flakes. These flakes tended to break away from the anode as the latter always underwent uneven dissolution. If there was any chance of a large piece of copper breaking away, and falling into the packed bed, the run was stopped, the anode removed and trimmed, then replaced and the run was allowed to continue.

A check sample was then taken from the screened grit.

6.9. Calculations

Six samples of coated grit were collected. This collection comprised the four samples taken during the run, plus the check sample taken from the screened grit, plus a sample taken from the nickel coated grit at the beginning of the run. The percentage metal coat on these samples was then determined.

The procedure adopted in determining the percentage metal coat was as follows: The samples were each washed three times with distilled water and then with ethanol. They were dried, and their weights determined. The metal coat was then removed by heating the sample of coated grit in a dilute solution of nitric acid for 15 minutes. The de-coated grit was washed three times with water and then with ethanol. The sample was dried and weighed.

For each of the samples the following value was determined:

$$\% \text{ Metal Coat } (P_{\Delta n}) = \frac{(\Delta_{sn} + M_{sn}) - \Delta_{sn}}{\Delta_{sn}} \times \frac{100}{1}$$

$$= \frac{M_{sn}}{\Delta_{sn}} \frac{100}{1} \quad \ldots\ldots\ldots\ldots \quad (7)$$

Δ_{sn} was the weight of uncoated grit in the sample (gm).

M_{sn} was the weight of metal in the sample (gm)

The subscript n denotes the position in the chronological sequence in which the sample was collected.

$(\Delta_{sn} + M_{sn})$ was the initial weight of the sample (gm).

From the value $P_{\Delta n}$ the value $P_{\Delta Mn}$ was calculated. $P_{\Delta Mn}$ was defined as:

$$P_{\Delta Mn} = \frac{M_{sn}}{\Delta_{sn} + M_{sn}} \times \frac{100}{1} \quad \ldots\ldots\ldots \quad (8)$$

Thus it was defined as the amount of metal present in the sample expressed as a percentage of the total weight of the coated sample.

From (7) $$\Delta_{sn} = \frac{100\ M_{sn}}{P_{\Delta n}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (9)$$

Substituting (9) in (8)

$$P_{\Delta Mn} = \frac{M_{sn} \times 100}{\left[\frac{100\ M_{sn}}{P_{\Delta n}} + M_{sn}\right]}$$

$$P_{\Delta Mn} = \frac{100\ P_{\Delta n}}{100 + P_{\Delta n}}$$

These percentages were obtained for each of the six samples. Thus obtaining $P_{\Delta 1}$ ... $P_{\Delta 6}$ and the corresponding $P_{\Delta M.}$ ... $P_{\Delta M6}$ values. $P_{\Delta 5}$ and $P_{\Delta 6}$ should agree to within 1% as they are samples taken from the same batch. The average of $P_{\Delta 5}$ and $P_{\Delta 6}$ was taken as the final percentage coat for the sampl :.

The actual mass of copper electrodeposited was then determined. The nomenclature used was as given below:

M_n was the weight of metal present in the bed when sample n was taken (gm).

Δ_n was the weight of diamond present in the bed when sample n was taken (gm).

T_n was the total weight of diamond plus metal in the bed at the time sample n was taken (gm).

D_n was the total weight of copper electrodeposited up to the time sample n was taken (gm).

$$M_1 = \frac{P_{\Delta M1}\ T_1}{100}$$

$$\Delta_1 = T_1 - M_1$$

The first total weight to be recorded was T_1 but this value was known as it was weighed out at the beginning of the run. This value for each run was 18.000 ± 0.003 gm.

D was zero as no copper had been deposited at this stage.

$$M_2 = \frac{\Delta_1\ P_{\Delta 2}}{100}$$

$$D_2 = M_2 - M_2$$

$$\Delta_2 = \Delta_1 - \Delta_{s2}$$

Thus the amount of diamond in the cell was decreased by the amount removed in the sample.

$$T_2 = \Delta_1 + M_2$$

Similarly $$M_2 = \frac{\Delta_2\ P_{\Delta 3}}{100}$$

$$D_3 = M_2 - M_1$$

$$\Delta_s = \Delta_2 - \Delta_{s3}$$

$$T_3 = \Delta_2 + M_3$$

etc.

The total weight of diamond removed from the cell during a run was approximately 1 gm.

6.10. Density Determinations

The density of the nickel coated grit and of the copper coated grit was then determined. The S.G. bottle technique for density determinations was used. The standard procedure for this technique was followed. Between 7 and 10 gm of sample was used for each determination. On adding distilled water to the dried sample in the S.G. bottle, it was found that numerous air bubbles would adhere to the particles. It was impossible to remove all these bubbles and thus erroneous results were obtained. In order to rectify this matter the following procedure was adopted. One or two drops of a wetting agent ("Teepol") were added to 500 ml of distilled water. This dilute solution was then used in place of the distilled water.

Duplicate density determinations were carried out on each nickel and each copper coated grit sample. The average variation among duplicate sets was ± 0.01, the highest being ± 0.04 . The average value of each of these sets was reported. See Appendix 2 for the results.

7.0. RESULTS

The results from Run 9 (Table 1) are presented as a typical set of data.

The total cell current is recorded in column two. This value was kept constant as far as possible. In this case it remained constant throughout the run. However, the results from a few of the other runs show that the current underwent a step-wise increase

until the desired value was reached. This step-wise increase was necessitated by the limited output of the rectifier used.

In column three the potential drop of the cell is recorded. This is the potential drop between the anode and the cathode, the latter being the pulsating fluidised bed plus the carbon rod.

The limits of accuracy of the flow rate is within 5%.

The Percentage Bed Expansion recorded in column seven is calculated as follows:

$$\text{Percentage Bed Expansion} = \frac{\text{S.B.V.}}{\text{E.B.V.}} \times \frac{100}{1}$$

The Total Theoretical Mass of Metal Deposited (Column 11) is an accumulative quantity and is calculated from Faraday's Law.

$$\text{Metal Deposited (gm)} = \frac{Itx}{F}$$

I is the current in amps.

t is the time for which this current flowed, in sec.

x is the equivalent weight of copper.

F is the Faraday(96,490 ± 2.4 amp-sec.)

The Cathode Efficiency (Column 13) is obtained as follows:

$$\text{Cathode Efficiency (\%)} = \frac{\text{Actual Mass Metal Deposited x 100}}{\text{Total Theoretical Mass Metal Deposited}}$$

The remainder of the Table is self explanatory.

Graph 1 is a plot of total weight of copper electrodeposited up to time t (gm) versus time t (Hrs.)

Graph 2 is a plot of Rate of Plating ($\frac{dm}{dt}$, in gm/hr) versus Total Mass of the Bed at time t (gm).

TABLE 1

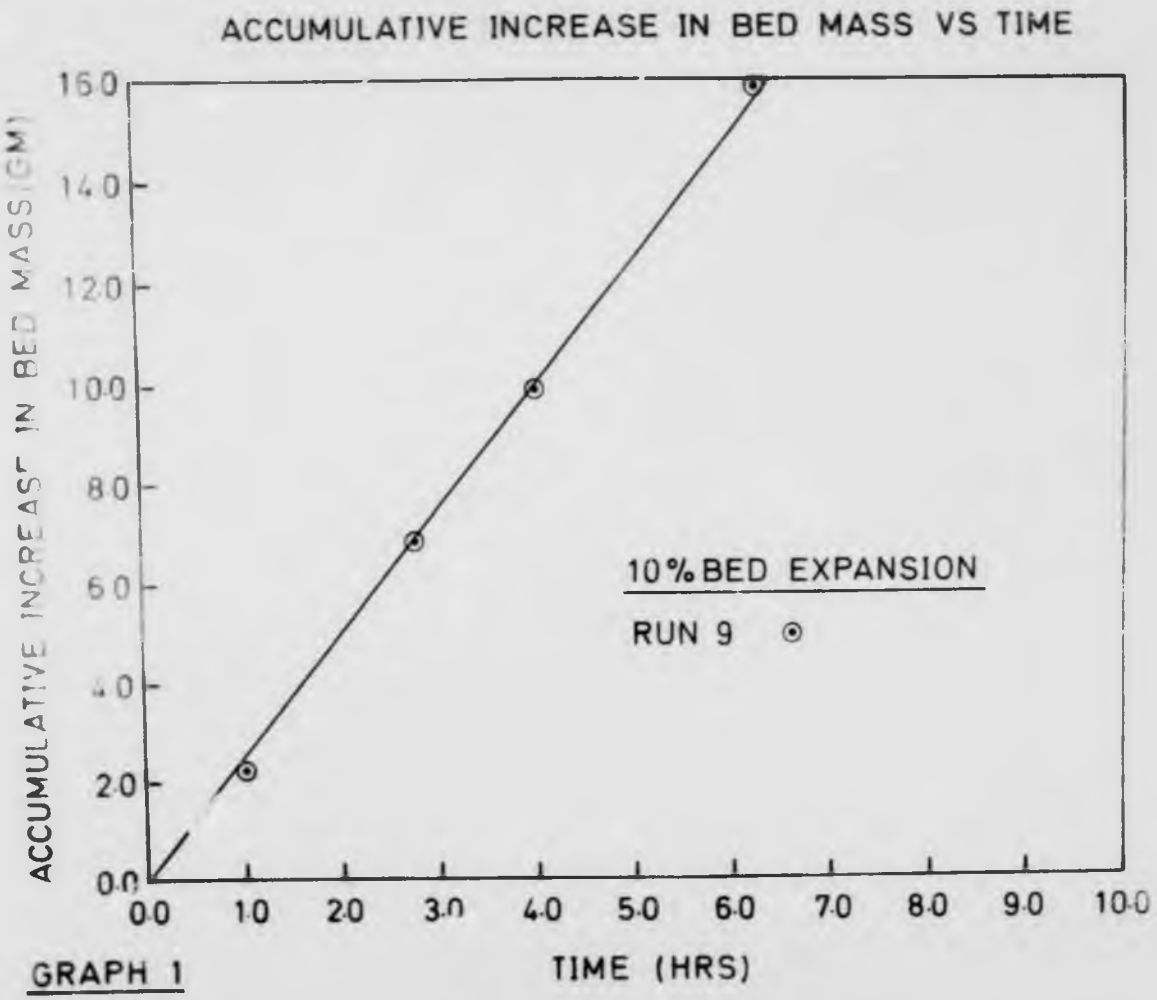
RESULTS OF RUN 9

Time (hr)	Current (Amps.)	Potential (volts)	Flow Rate (L/min)	S.B.V. (cm^3)	E.B.V. (cm^3)	% Bed Exp.	Sol. Temp (°C)	Total Mass (gm)	% Metal coat	Total Theor. Metal Dep. (gm)	Total Actual Metal Dep. (gm)	Cathode Eff. (%)	$\frac{dm}{dt}$
0.00	2.25	1[illegible].4	0.116	12.87	14.01	9	24.0	18.000	5.95	0.00	0.00	-	-
0.50	2.25	11.8	0.125	13.25	14.51	10	31.0						
0.50	2.25	11.8	0.129	13.25	14.51	10	31.0						
1.00	2.25	11.0	0.144	13.50	14.77	9	33.5	20.222	19.02	2.66	2.22	83	2.22
1.00	2.25	11.8	0.144	13.38	14.51	9	32.0						
1.50	2.25	11.2	0.155	13.50	14.77	9	34.0						
1.50	2.25	11.2	0.157	13.38	15.15	13	33.5						
2.00	2.25	10.5	0.162	13.88	15.02	9	34.0						
2.00	2.25	10.8	0.171	13.88	15.27	10	33.5						
2.75	2.25	12.3	0.191	14.14	15.53	10	34.5	24.779	46.60	7.33	6.86	94	2.47
2.75	2.25	12.4	0.175	13.88	15.27	10	33.0						
3.50	2.25	12.3	0.179	14.51	15.79	9	34.5						
3.50	2.25	12.3	0.184	14.39	15.79	10	34.5						

TABLE 1 (Cont.)

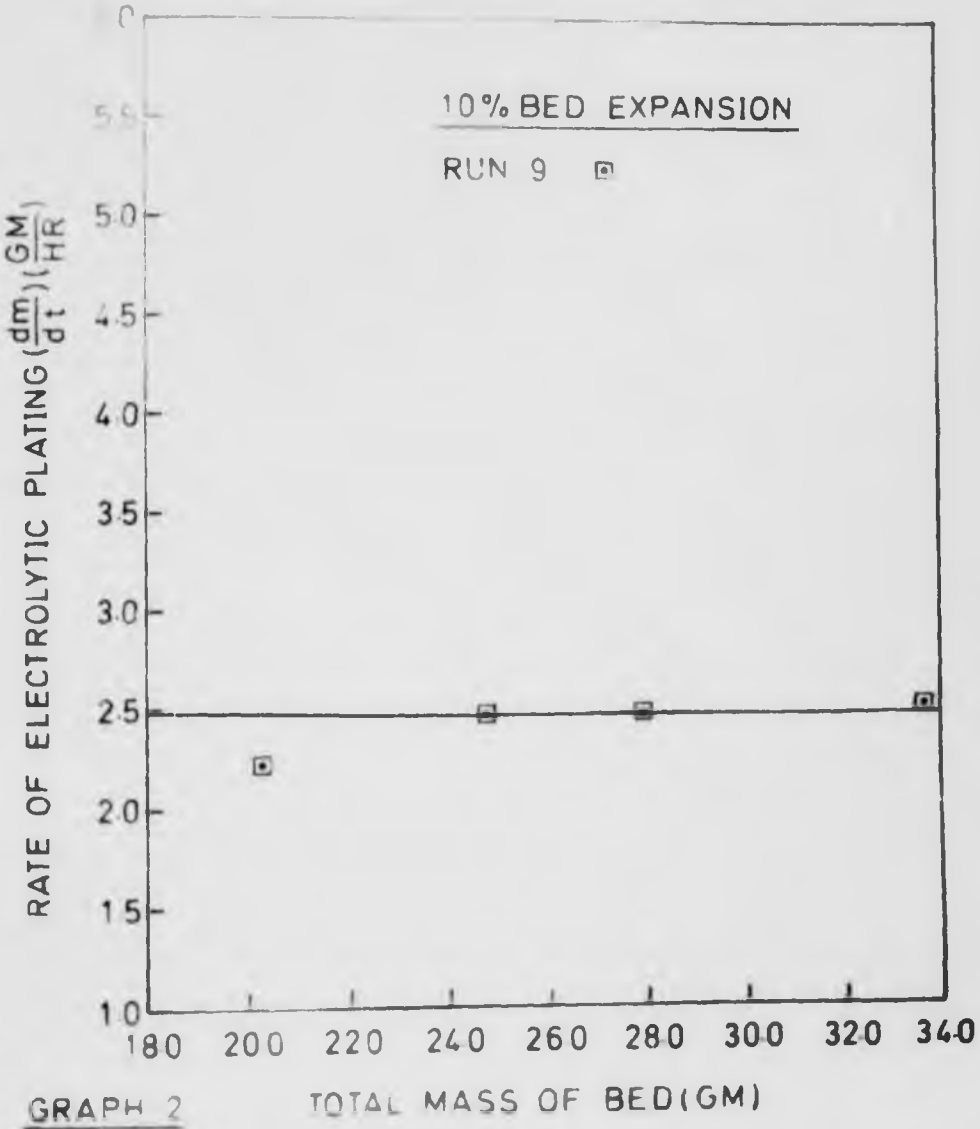
Time (hr)	Current (Amps.)	Potential (volts)	Flow Rate (L/min)	S.B.V. (cm)	E.B.V. (cm)	% Bed Exp.	Sol. Temp (°C)	Total Mass (gm)	% Metal coat	Total Theor. Metal Dep. (gm)	Total Actual Metal Dep. (gm)	Cathode Eff. (%)	$\frac{dm}{dt}$
4.00	2.25	12.2	0.191	14.77	16.05	9	35.0	27.936	64.71	10.66	9.96	93	2.48
4.00	2.25	12.4	0.171	14.14	15.53	10	33.5						
4.75	2.25	13.8	0.178	14.64	16.05	10	35.0						
4.75	2.25	13.8	0.181	14.51	16.05	10	35.0						
5.65	2.25	13.5	0.186	15.27	16.57	9	35.0						
5.65	2.25	11.5	0.194	15.27	16.57	9	35.0						
6.25	2.25	12.7	0.205	15.27	16.83	10	35.0	33.67	100.70	16.66	15.88	95	2.51

Copper coat density (gm/ml) = 8.59


ACCUMULATIVE INCREASE IN BED MASS VS TIME
ACCUMULATIVE INCREASE IN BED MASS (GM)
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
10% BED EXPANSION
RUN 9 ⊙
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
TIME (HRS)

GRAPH 1

RATE OF ELECTROLYTIC PLATING VS TOTAL MASS OF BED



GRAPH 2

At the end of each run, the coated particles were photographed at magnifications of 120X and 1200X. These are presented with the remainder of the plating results in Appendix 2.

8.0. ANALYSIS AND DISCUSSION OF RESULTS

The results in Appendix 2 indicate that, apart from the initial plating period when erratic readings were obtained, the rate of copper deposition is constant during the course of a run. It can thus be assumed that the mass and hence surface area of the particles does not markedly affect this rate.

Table 2 has been compiled from the 24 runs with each pair averaged and grouped according to bed expansion and current. The most significant factor to emerge is that the cathode efficiency does not show any consistent trend and remains reasonably constant with a mean value of approximately 93%. This compares with a mean value of about 97% obtained on the barrel system under similar conditions.

The density of the copper coat also remained reasonably constant over the range of variables employed. The average value of 8.45 gm/cm^3 is greater than that resulting from coatings in the barrel system where the highest value attained was in the region of 7.7 gm/cm^3. It has been postulated[17] that grinding efficiency improves with increased metal coat density.

The final two columns in Table 2 have been constructed in an effort to estimate the effect of the experimental parameters on the area of the particles on which metal is depositing at any instant in time. To calculate this effective cathode area it would be necessary to know the weighted mean anode to cathode distance based on the distribution of current flux, the equivalent conductivity of the

TABLE 2

Bed Exp (%)	Current (Amps)	Potential (Volts)	Cathode Eff. (%)	Copper Coat Density (gm/cm^3)	Anode to Cathode Distance (cm)	Effective Cathode Area (cm^2)
5	1.50	10.6	91	8.28	3.0	10.7
5	2.25	13.5	92	8.43	3.2	13.2
5	3.00	15.2	98	8.21	3.3	16.4
10	1.50	8.6	91	8.76	3.1	13.7
10	2.25	11.7	95	8.56	3.6	17.5
10	3.00	13.3	94	8.48	3.9	22.3
15	1.50	10.2	92	8.51	3.6	13.5
15	2.25	14.1	93	8.26	3.5	14.0
15	3.00	15.9	88	8.40	3.6	16.8
20	1.50	10.7	99	8.37	3.5	12.5
20	2.25	14.5	91	8.66	3.5	13.7
20	3.00	17.6	93	8.42	3.6	15.4

solution and the potential difference between the anode and the surface of the particles where plating is taking place. To simplify this calculation the following assumptions are made:

1. Metal is deposited only on the surface of particles which are actually in physical contact with the current feeder. Hence the potential of the cathode is essentially the same as that of the current feeder.

2. The anode to cathode separation is taken as the distance between the lower rim of the anode and the upper end of the current feeder, which is the line of maximum current density. Although it is not claimed that this assumption will give a very precise result in the calculation of effective cathode area, it should nevertheless give a reasonable indication of the relative variation of this parameter with operating conditions.

The areas were calculated as follows:

$$\text{Area of the cathode } (cm^2) = \frac{Iy}{PHE}$$

I is electric current (amps)

y is the anode to cathode distance (cm)

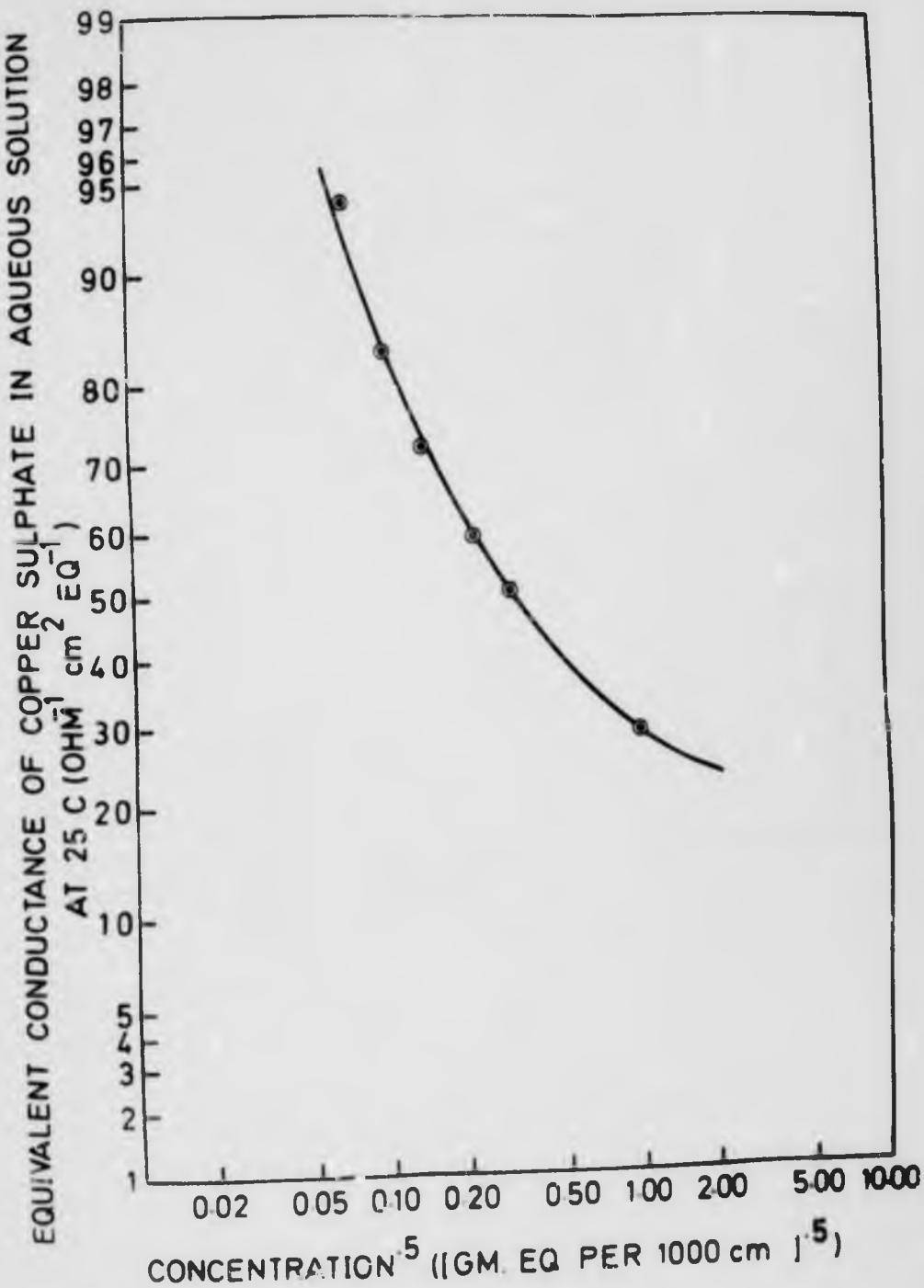
P is the electric potential (volts)

H is the equivalent conductance of copper sulphate in aqueous solution ($ohm^{-1}\ cm^2\ eq^{-1}$)

E is the concentration of copper sulphate (gm eq. per 1000 cm^3). For these runs E = 1.6 gm eq. per 1000 cm^3.

Due to the lack of data for the equivalent conductance of copper sulphate at concentrations greater than 1.0N and temperatures above

EQUIVALENT CONDUCTANCE OF COPPER SULPHATE VS CONCENTRATION$^{.5}$



GRAPH 3

25°C, the value at 25°C was chosen for the calculations of the cathode areas. The constant value for H used in these calculations was read off Graph 3. The information used to plot Graph 3 was obtained from Barrow[18] and the "Handbook of Chemistry and Physics."[19]

The cathode area was found to increase with current at each bed expansion.

The coat roughness as shown by Plates 5A, B, C and D (See Appendix 2) varies with the bed expansion of the run, the greater the bed expansion the smoother the coat. However, no relation was found between coat roughness and density. This seems to indicate that the smoothing mechanism is purely mechanical. The nodules shown in Plate 5A (these particles were coated in a bed of 5% expansion) were not formed in a bed undergoing 20% expansion. The possible reason for this was that the violent movement of the particles in the bed caused them to collide with each other with such force that any protruding nodules of copper would be hammered flat. (See Plate 5D)

The pulsating-fluidised bed system therefore, enables batches of diamond to have copper coats deposited on them which are identical in all respects except for their roughness. The inability of the barrel system to coat the particles in this way gives the pulsating-fluidised bed system a decided advantage, as grit coated in the latter system can be used to accurately test the theory concerning keying between the metal coat and the resin bond.

The hydrodynamics of the pulsating-fluidised bed system does not allow the particles to reside adjacent to one another, or in contact with the current feeder long enough for agglomeration or adherence to the current feeder to take place. The two major problems encountered in the barrel system are thus eliminated. The pulsating-fluidised

bed system enables 18 gm batches of diamond to be successfully coated, whereas the smallest amount the barrel system can handle is 50 gm. Current densities of 0.17 A/gm are attainable in the pulsating-fluidised bed system compared with only 0.04 A/gm in the barrel system.

9.0. SCALE-UP

Scale-up from the fluidisation point of view should present no problems. The present system has an inside cell diameter of 1.90 cm and with a batch of 18 gm of diamond grit the bed height varies between approximately 5 and 8 cm. A cell accommodating 600 gm of diamond (this is the upper limit of amounts plated in the barrel system - see Section 2.0), need have an inside diameter of only 8 cm. Fluidised under the conditions used in these experiments the bed height would vary between 10 and 16 cm. Fluidisation of beds of comparable dimensions is common practice and a reasonable amount of work has been done on systems in this size range.[13,14] The same random particle movement and good mixing should be achieved in this larger system.[15,16] It has been reported[4] that fluidisation performance decreases as the bed height-to-diameter ratio increases. However, for the larger system this ratio will in fact be lower than for the present system (i.e. 1.7 as against 2.5). This ratio alone is not sufficient to define the performance of a fluidised system as performance also seems to deteriorate as the vessel diameter increases. The dimensions of this large cell could however, be optimised with little difficulty.

From the electrical point of view problems are envisaged In the larger system the potential drop across the bed will be proportionally greater. Thus potential drops of well over 18V will occur. (18.4V was the upper potential used during these experiments).

However, on obtaining a suitable permeable material, a two compartment system outlined in Figure 9 could be constructed. The anode would then be able to encircle the cathode compartment and this would facilitate higher currents at lower potentials. The electrical flux lines between electrodes in this system would be undistorted compared to the distorted pattern obtained in the present system. (Figure 5).

10.0. CONCLUSION

The pulsating-fluidised bed system showed the following advantages over the barrel system:

1. The problem of agglomeration was eliminated simply by the hydrodynamic properties of the fluidised bed system.

2. The problem of adherence of the diamond particles to the current feeder was overcome by causing this fluidised bed to pulsate.

3. Current densities of more than 4 times those used in the barrel system were used in this system.

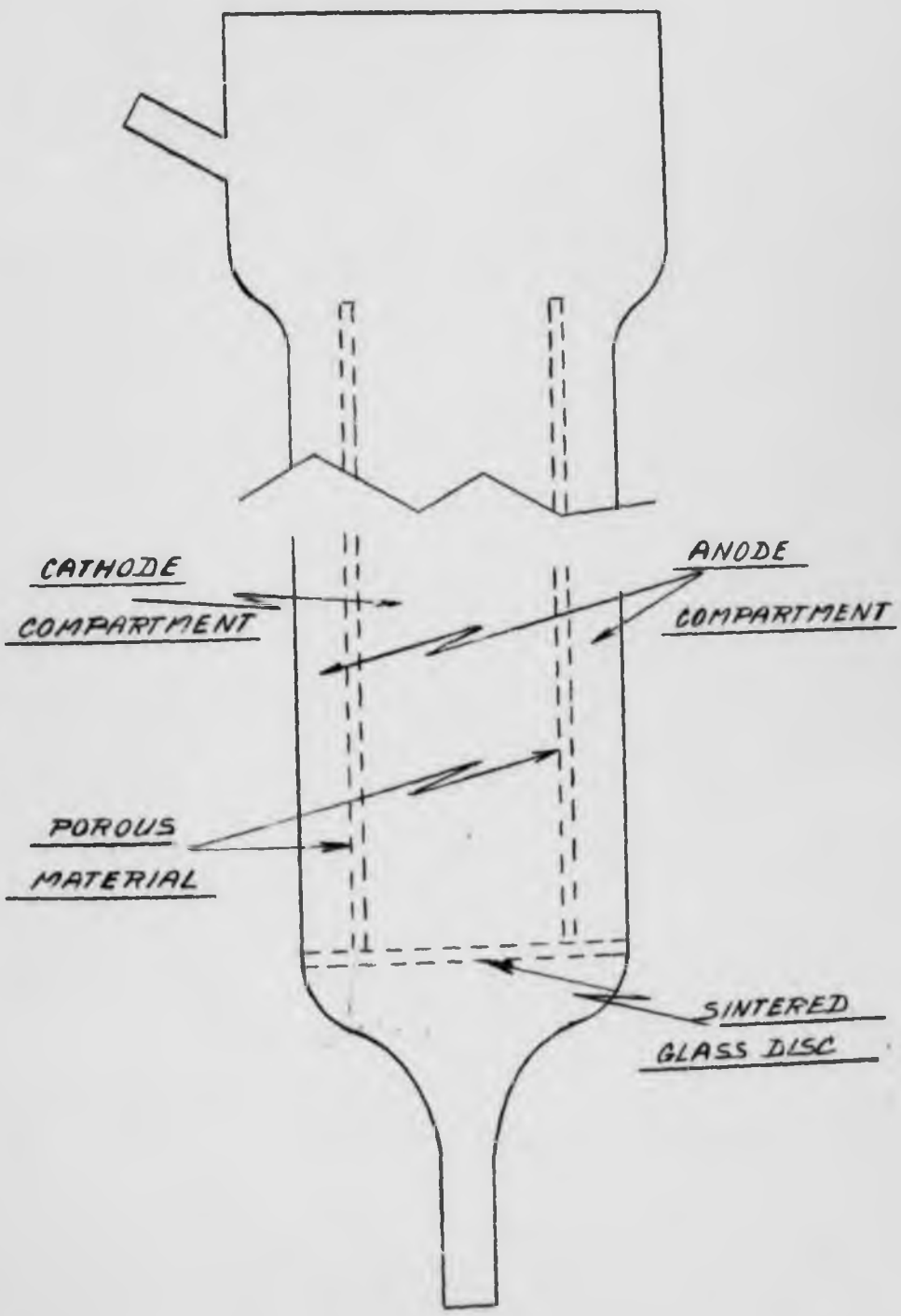
4. Small batches of diamonds each weighing 18 gm were handled with ease.

5. Increased densities were obtained in the copper coat.

6. It is possible to vary the roughness of the copper coat.

FIG. 9

TWO COMPARTMENT SYSTEM



LIST OF SYMBOLS

Unless specifically stated otherwise in the text, the symbols used have the following meanings:

A	surface area of arbitrarily shaped particle.
A_p	surface area of spherical particle having the same volume as a particle with surface area A
a	experimental constant.
C	experimental constant.
C_B	concentration of the ion in the bulk of the solution.
C_e	concentration of the ion in contact with the electrode.
D_A	diffusivity of species A.
D_E	effective diffusivity.
D_n	total weight of copper deposited up to the time sample n is taken.
D_p	particle diameter.
D_t	circular conduit diameter.
E	concentration of copper sulphate in aqueous solution.
F	Faraday (96,490 ± 2.4 amp. sec.)
g	Acceleration of gravity.
H	equivalent conductance of copper sulphate in aqueous solution.
I	electric current.
K	proportionality constant.
L	bed height
M_n	mass of metal present in the bed when sample n is taken.
M_{sn}	mass of metal in sample n.
N_A	molar rate of diffusion of species A per unit area.

LIST OF SYMBOLS (Cont.)

p	electric potential
Q	volumetric flow rate.
r	outer radius of annular conduit.
r_i	inner radius of annular conduit.
S_c	Schmidt Number
T_n	total weight of diamond plus metal in the bed at the time sample n is taken.
U_o	superficial velocity of fluidising fluid at incipient fluidisation.
V	volume of a spherical particle.
W_A	mobility of the ion of species A.
x	equivalent weight of copper.
y	anode to cathode distance
Z_A	valence of the ion of species A
Δ_n	weight of diamond present in the bed when sample n is taken.
ΔP	change in pressure.
Δ_{sn}	weight of diamond in sample n.
δ	thickness of the diffusion layer.
δ_o	thickness of the hydrodynamic boundary layer.
εo	bed voidage fraction at incipient fluidisation.
μ	fluid viscosity.
ρ	fluid density.
ρ_s	diamond density.
$\frac{\partial V}{\partial y}$	electrical potential gradient.

LIST OF ABBREVIATIONS

E.B.H.	Expanded Bed Height.
E.B.V.	Expanded Bed Volume.
S.B.H.	Static Bed Height.
S.B.V.	Static Bed Volume.
S.D.A.	Saw Diamond Abrasive.

REFERENCES

1. Bockris, J.O'M., and Reddy, A.K.N., "Modern Electrochemistry", Plenum Press, New York, 1970, 974, 1052.

2. Lowenheim, F.A., "Modern Electroplating", John Wiley & Sons, N.Y., 2nd Edition, 1966, 181.

3. Levich, V.G., "Physico-Chemical Hydrodynamics", Prentice Hall, 1962.

4. Shuster, W.W., and Kisliak, P., 1952, Chem. Eng. Prog., 48, 455.

5. Grohse, E.W., 1955, A.I. Ch. E. Journal, 1, (3), 358.

6. Kozeny, J., 1927, "Uber kapillare Leitung des Wassers in Boden, S.B. Akad. Wiss. Wien., Abrt. IIa, 136, 271.

7. Carman, P.C., 1937, Trans. Instn. Chem. Eng. Lond., 15, 150.

8. Carman, P.C., "Flow of Gases Through Porous Media", Butterworths, London, 1956.

9. Lewis, W.K., Gilliland, E.R., and Bauer, W.C., 1949, Ind. Chem. Eng., 41, 1104.

10. Leva, M., Weintaub, M., Grummer, M., Pollchik, M., and Storch, H.H., 1951, U.S. Bureau Mines Bull., 504.

11. Leva, M., "Fluidization", McGraw-Hill Book Co., 1959.

12. Lamb, V.A. et al., 1970, J. Elec. Chem. Soc., 117 (9), 291C.

13. Bertel Anderson, K.E., 1961, Chem. Eng. Sci., 15, 276.

14. Le Goff, P. et al., 1969, Ind. & Eng. Chem., 61 (10), 8.

REFERENCES (Cont.)

15. Scarlet, B., and Blogg, M.J., "The Motion and Distribution of Particles in a Liquid Fluidized Bed", Proc. of Int. Sym. on Fluidization, Eindhoven, 1967.

16. Rowe, P.N., and Partridge, B.A., "Movement Caused by Bubbles in a Fluidised Bed", Proc. of the Sym. on the Interaction between Fluids and Particles, London, 1962.

17. Simpson, J.D., Private Communication.

18. Barrow, G.M., "Physical Chemistry", Mc Graw-Hill Book Co., 2nd Edition, 1966.

19. "handbook of Chemistry and Physics", The Chemical Rubber Publishing Co., 44th Edition, 1963.

APPENDIX 1

The term current density as used here, is really a pseudo current density, as the actual current density at any given moment is impossible to determine. The reason for this is that the cathode area is comprised of the total surface area of the diamond particles in contact with the current feeder at a particular moment. As this value is impossible to determine, the exact current density is likewise impossible to determine. However, for a given particle size, the mass of the particles is directly related to the surface area of these particles. Thus current per unit mass is directly related to current density and a low current per unit mass would imply a low current density and vice versa.

APPENDIX 2

RUN 1

BED EXPANSION = 5%

Time (hr)	Current (Amps.)	Potential (volts)	Flow Rate (L/min)	S.B.V. (cm^3)	E.B.V. (cm^3)	% Bed Exp.	Sol. Temp (°C)	Total Mass (gm)	% Metal coat	Total Theor. Metal Dep. (gm)	Total Actual Metal Dep. (gm)	Cathode Eff. (%)	$\frac{dm}{dt}$
0.00	1.50	10.6	0.057	11.25	11.99	6	23.0	18.000	5.76	0.00	0.00	-	
0.50	1.50	9.5	0.053	11.63	11.99	3	30.0						
0.50	1.50	10.5	0.056	11.63	12.14	4	30.0						
1.00	1.50	8.8	0.055	11.76	12.14	3	30.0	19.558	14.94	1.77	1.56	88	1.558
1.00	1.50	9.4	0.060	11.76	12.27	4	30.0						
1.75	1.50	8.0	0.062	11.51	12.40	6	30.0						
1.75	1.50	8.1	0.056	11.51	12.27	6	30.0						
2.50	1.50	7.6	0.055	11.76	12.40	5	30.0						
2.50	1.50	7.6	0.057	11.76	12.40	5	30.0						
3.25	1.50	8.2	0.055	12.52	12.90	3	30.0						
3.25	1.50	9.6	0.080	12.52	13.16	5	30.0						
3.75	1.50	9.6	0.080	12.52	13.28	6	29.5	24.458	45.28	6.66	6.64	100	1.722
3.75	1.50	10.0	0.082	12.40	13.03	5	29.5						
4.50	1.50	8.8	0.080	12.78	13.28	4	30.0						

RUN 1 (Cont.)

Time (hr)	Current (Amps.)	Potential (volts)	Flow Rate (L/min)	S.B.V. (cm^3)	E.B.C. (cm^3)	% Bed Exp.	Sol. Temp (°C)	Total Mass (gm)	% Metal coat	Total Theor. Metal Dep. (gm)	Total Actual Metal Dep. (gm)	Cathode Eff. (%)	$\frac{dm}{dt}$
4.50	1.50	8.8	0.096	12.78	13.54	6	30.0						
5.25	1.50	9.6	0.094	13.03	13.86	6	30.5						
5.25	1.50	10.2	0.104	13.03	13.92	7	30.5						
6.00	1.50	10.0	0.196	13.28	14.04	6	31.0						
6.00	1.50	11.6	0.101	13.28	14.04	6	31.0						
6.50	1.50	11.6	0.096	13.54	14.04	4	31.0						
6.50	1.50	10.8	0.116	13.54	14.30	5	31.0						
7.00	1.50	11.4	0.116	13.54	14.55	7	30.1	30.046	82.01	12.44	12.55	101	1.720
7.00	1.50	11.4	0.119	13.54	14.30	7	30.1						
7.75	1.50	13.0	0.118	13.79	14.49	5	30.8						
7.75	1.50	10.3	0.119	13.79	14.49	5	30.8						
8.50	1.50	10.8	0.116	14.04	14.68	4	30.8						
8.50	1.50	10.8	0.118	14.04	14.68	4	30.8						
9.00	1.50	9.8	0.116	14.04	14.80	5	30.8						
9.00	1.50	10.1	0.118	14.04	14.80	5	30.8						
9.50	1.50	10.3	0.116	14.11	14.84	5	30.8	33.040	103.39	16.88	15.81	94	1.583

Density (gm/cm^3)

Nickel coat = 7.05 Copper Coat = 8.34

RUN 2

BED EXPANSION = 5%

Time (hr)	Current (Amps.)	Potential (volts)	Flow Rate (L/min)	S.B.V. (cm^3)	E.B.V. (cm^3)	% Bed Exp.	Sol. Temp (°C)	Total Mass (gm)	% Metal coat	Total Theor. Metal Dep. (gm)	Total Actual Metal Dep. (gm)	Cathode Eff. (%)	$\frac{dm}{dt}$
0.00	1.5	18.3	0.077	11.76	12.52	7	23.0	18.000	4.65	0.00	0.00		
0.17	1.5	17.6	0.080	11.76	12.40	5	25.9						
0.50	1.5	14.0	0.076	11.76	12.40	5	30.0						
0.50	1.5	13.8	0.078	11.76	12.40	5	30.0						
1.00	1.5	10.8	0.075	11.63	12.40	6	31.7	19.337	12.40	1.77	1.33	75	1.337
1.00	1.5	10.8	0.060	11.38	12.02	6	31.5						
1.75	1.5	11.2	0.056	11.51	11.99	4	32.1						
1.75	1.5	9.5	0.067	11.51	12.14	5	32.1						
2.50	1.5	9.6	0.066	11.63	12.14	4	31.2						
2.50	1.5	10.0	0.067	11.6[illegible]	12.14	4	31.2						
3.25	1.5	9.2	0.066	12.02	12.40	3	31.0						
3.25	1.5	9.2	0.078	12.02	12.65	5	31.0						
3.75	1.5	12.2	0.082	12.14	12.90	6	30.0	23.130	36.11	6.66	5.33	80	1.368
3.75	1.5	12.4	0.075	12.02	12.78	6	30.0						
4.50	1.5	12.0	0.074	12.14	12.78	5	32.0						
4.50	1.5	12.0	0.074	12.14	12.78	5	32.0						
5.25	1.5	12.8	0.072	12.40	12.84	4	33.0						
5.25	1.5	14.4	0.075	12.52	13.03	4	33.0						

RUN 2 (Cont.)

Time (hr)	Current (Amps.)	Potential (volts)	Flow Rate (L/min)	S.B.V. (cm^3)	E.B.V. (cm^3)	% Bed Exp.	Sol. Temp (°C)	Total Mass (gm)	% Metal Coat	Total Theor. Metal Dep. (gm)	Total Actual Metal Dep. (gm)	Cathode Eff. (%)	$\frac{dm}{dt}$
6.00	1.5	12.8	0.075	12.65	13.28	5	33.0						
6.00	1.5	13.0	0.083	12.65	13.41	6	33.0						
7.00	1.5	13.9	0.081	13.03	13.48	3	33.6	28.094	67.42	12.44	10.51	84	1.442
7.00	1.5	11.2	0.082	12.65	13.23	5	33.6						
7.75	1.5	11.4	0.082	12.78	13.66	7	32.7						
7.75	1.5	12.0	0.078	12.78	13.48	5	32.7						
8.50	1.5	10.6	0.078	13.03	13.66	5	31.1						
8.50	1.5	11.0	0.080	13.03	13.66	5	31.1						
9.0	1.5	10.7	0.078	13.28	13.92	5	31.8						
9.00	1.5	11.0	0.080	13.28	13.92	5	31.8						
9.50	1.5	11.0	0.078	13.28	13.92	5	32.0	32.366	95.58	16.88	15.01	89	1.512

Density (gm/cm^3)

Nickel coat = 6.36 Copper coat = 8.21

RUN 3 BED EXPANSION = 5%

Time (hr)	Current (Amps.)	Potential (volts)	Flow Rate (L/min)	S.B.V. (cm^3)	E.B.V. (cm^3)	% Bed Exp.	Sol. Temp (°C)	Total Mass (gm)	% Metal coat	Total Theor. Metal Dep. (gm)	Total Actual Metal Dep. (gm)	Cathode Eff. (%)	$\frac{dm}{dt}$
0.00	2.25	18.4	0.044	11.13	11.99	7	22.6	18.000	5.07	0.00			
0.50	2.25	15.2	0.048	11.38	12.27	8	32.5						
0.50	2.25	14.9	0.060	11.38	12.14	7	32.5						
1.00	2.25	14.8	0.055	11.63	12.27	5	31.5	20.118	17.38	2 66	2.11	79	2.118
1.00	2.25	13.2	0.057	11.51	12.14	5	36.0						
1.75	2.25	12.8	0.056	12.02	12.40	3	36.5						
1.75	2.25	13.6	0.063	12.02	12.52	4	36.0						
2.25	2.25	13.2	0.060	12.78	13.16	3	36.5						
2.25	2.25	14.4	0.088	12.78	13.41	5	36.0						
2.75	2.25	14.4	0.088	13.28	13.54	2	36.0	24.296	43.39	7.33	6.48	88	2.289
2.75	2.25	15.2	0.063	12.78	12.90	1	36.5						
3.17	2.25	15.0	0.085	12.90	13.41	4	37.0						
3.50	2.25	14.4	0.086	13.54	13.79	2	36.0						
3.50	2.25	14.4	0.107	13.54	14.17	4	35.5						
4.00	2.25	13.8	0.109	13.54	14.30	5	34.0	26.539	60.78	10.66	9.16	86	2.134
4.00	2.25	13.2	0.116	13.41	14.17	5	34.0						

RUN 3 (Cont.)

Time (hr)	Current (Amps.)	Potential (volts)	Flow Rate (L/min)	S.B.V. (cm^3)	E.B.V. (cm^3)	% Bed Exp.	Sol. Temp (°C)	Total Mass (gm)	% Metal coat	Total Theor. Metal Dep. (gm)	Total Actual Metal Dep. (gm)	Cathode Eff. (%)	$\frac{dm}{dt}$
4.75	2.25	13.2	0.113	13.66	14.68	7	34.0						
4.75	2.25	14.8	0.092	13.66	14.17	4	34.0						
5.50	2.25	13.6	0.091	13.92	14.42	4	35.0						
5.50	2.25	14.6	0.094	13.92	14.68	5	35.0						
6.25	2.25	16.0	0.090	14.55	14.93	3	32.5	32.145	99.06	16.66	15.12	91	2.263

Density (gm/cm^3)

Nicke coat = 7.05 Copper coat = 8.82

RUN 4 BED EXPANSION = 5%

Time (hr)	Current (Amps.)	Potential (volts)	Flow Rate (L/min)	S.B.V. (cm^3)	E.B.V. (cm^3)	% Bed Exp.	Sol. Temp (°C)	Total Mass (gm)	% Metal coat	Total Theor. Metal Dep. (gm)	Total Actual Metal Dep. (gm)	Cathode Eff. (%)	$\frac{dm}{dt}$
0.00	2.25	18.4	0.085	12.14	12.97	7	23.0	18.001	5.78	0.00	0.00		
0.25	2.25	16.8	0.082	12.14	12.65	4	28.0						
0.50	2.25	15.8	0.076	12.02	12.85	7	32.4						
0.50	2.25	15.3	0.068	12.02	12.59	4	32.4						
1.00	2.25	17.7	0.064	11.99	12.85	7	37.8	20.374	19.72	2.66	2.37	89	2.373
1.00	2.25	14.6	0.043	11.63	12.21	5	37.8						
1.75	2.25	12.8	0.041	11.76	12.40	5	39.8						
1.75	2.25	11.0	0.041	11.76	12.40	5	39.8						
2.25	2.25	13.4	0.041	12.40	12.78	3	39.0						
2.25	2.25	15.8	0.045	12.40	12.90	4	38.8						
2.75	2.25	14.4	0.046	13.03	13.16	1	38.0	25.001	49.38	7.33	7.28	99	2.545
2.75	2.25	13.6	0.080	13.03	13.54	4	36.0						
3.50	2.25	13.6	0.076	13.54	13.66	1	37.0						
3.50	2.25	13.4	0.101	13.54	14.04	4	36.0						
4.00	2.25	13.8	0.104	14.04	14.42	3	37.0	27.060	65.12	10.66	9.68	91	2.264

RUN 4 (Cont.)

Time (hr)	Current (Amps.)	Potential (volts)	Flow Rate (L/min)	S.B.V. (cm^3)	E.B.V. (cm^3)	% Bed Exp.	Sol. Temp (°C)	Total Mass (gm)	% Metal coat	Total Theor. Metal Dep. (gm)	Total Actual Metal Dep. (gm)	Cathode Eff. (%)	$\frac{dm}{dt}$
4.00	2.25	11.8	0.115	13.92	14.42	4	36.5						
4.75	2.25	11.4	0.113	14.42	14.68	2	36.5						
4.75	2.25	12.8	0.134	14.42	15.18	5	36.0						
5.50	2.25	10.6	0.139	14.42	15.13	5	34.5						
5.50	2.25	11.0	0.140	14.42	15.13	5	34.3						
6.25	2.25	10.6	0.144	14.42	15.5	7	34.0	33.482	107.91	16.66	16.38	98	2.476

Density (gm/cm^3)

Nickel coat = 7.04 Copper coat = 8.04

RUN 5 BED EXPANSION = 5%

Time (hr)	Current (Amps.)	Potential (volts)	Flow Rate (L/min)	S.B.V. (cm^3)	E.B.V. (cm^3)	% Bed Exp.	Sol. Temp. (°C)	Total Mass (gm)	% Metal coat	Total Theor. Metal Dep. (gm)	Total Actual Metal Dep. (gm)	Cathode Eff. (%)	$\frac{dm}{dt}$
0.00	1.00	8.0	0.086	11.76	12.97	10	23.9	18.000	5.18	0.00	0.00		
0.08	1.00	8.0	0.081	11.76	12.65	8	24.3						
0.17	1.00	9.0	0.074	11.76	12.40	6	24.8						
0.25	1.50	12.3	0.076	11.76	12.46	6	25.6						
0.33	3.00	18.0	0.076	11.76	12.46	6	26.2						
0.50	3.00	14.4	0.075	11.38	12.52	10	31.0	18.722	9.43	1.03	0.72	70	1.445
0.50	3.00	13.2	0.055	11.25	11.99	6	33.0						
1.00	3.00	14.8	0.055	11.76	12.40	6	37.1						
1.00	3.00	16.4	0.082	11.76	13.03	11	38.2						
1.50	3.00	17.8	0.077	12 27	13.28	8	43.0						
1.50	3.00	14.2	0.082	12 27	13.28	8	43.0						
2.00	3.00	15.6	0.081	12.78	13.60	7	43.2	23.562	39.57	6.37	5.79	91	2.781
2.00	3.00	15.3	0.089	12.52	13.66	9	43.2						
2.50	3.00	15.6	0.088	13.28	13.98	5	44.0						
2.50	3.00	14.8	0.092	13.28	14.11	7	44.0						
2.58	3.00	14.8	0.116	13.28	14.74	11	43.9						
3.25	3.00	16.0	0.116	14.04	15.12	8	43.8	28.169	68.69	10.81	10.58	98	3.129

RUN 5 (Cont.)

Time (hr)	Current (Amps.)	Potential (volts)	Flow Rate (L/min)	S.B.V. (cm^3)	E.B.V. (cm^3)	% Bed Exp.	Sol. Temp (°C)	Total Mass (gm)	% Metal coat	Total Theor. Metal Dep. (gm)	Total Actual Metal Dep. (gm)	Cathode Eff. (%)	$\frac{dm}{dt}$
3.25	3.00	14.0	0.118	13.92	14.87	7	43.8						
3.50	3.00	15.5	0.149	14.42	15.56	8	42.0						
4.00	3.00	15.4	0.150	14.80	16.07	8	42.4						
4.00	3.00	15.4	0.151	14.80	16.07	8	42.4						
4.50	3.00	16.3	0.150	15.31	16.26	6	43.1	72.329	96.82	15.26	15.00	98	3.184

NOTE: At the current of 3.00A dendrite growth on the bed surface was so rapid that a bed expansion of greater than 5% had to be used.

Density (gm/cm^3)

Nickel coat = 5.89 Copper coat = 8.02

RUN 6 BED EXPANSION = 5%

Time (hr)	Current (Amps.)	Potential (volts)	Flow Rate (L/min)	S.B.V. (cm^3)	E.B.V. (cm^3)	% Bed Exp.	Sol. Temp (°C)	Total Mass (gm)	% Metal coat	Total Theor. Metal Dep. (gm)	Total Actual Metal Dep. (gm)	Cathode Eff. (%)	$\frac{dm}{dt}$
0.00	1.00	8.2	0.094	11.38	12.97	14	24.0	18.000	6.75	0.00	0.00		
0.08	1.50	13.0	0.088	11.38	12.78	13	24.3						
0.17	2.00	16.2	0.085	11.38	12.65	11	25.9						
0.30	3.00	17.3	0.085	11.38	12.78	13	26.1						
0.50	3.00	15.5	0.054	11.51	12.46	8	34.6	19.344	14.73	1.27	1.34	106	2.688
0.50	3.00	16.2	0.053	11.38	12.27	8	35.0						
1.00	3.00	14.4	0.047	11.76	12.40	5	41.0						
1.00	3.00	16.3	0.066	11.76	12.72	8	41.3						
1.42	3.00	15.7	0.066	12.40	12.97	5	43.1						
1.42	3.00	14.8	0.083	12.40	13.35	8	43.1						
1.63	3.00	14.9	0.092	12.40	13.66	10	42.1						
2.00	3.00	15.4	0.092	13.16	13.86	5	42.8	24.550	47.58	6.60	6.77	103	3.275

RUN 6 (Cont.)

Time (hr)	Current (Amps.)	Potential (volts)	Flow Rate (L/min)	S.B.V. (cm^3)	E.B.V. (cm^3)	% Bed Exp.	Sol. Temp (°C)	Total Mass (gm)	% Metal coat	Total Theor. Metal Dep. (gm)	Total Actual Metal Dep. (gm)	Cathode Eff. (%)	$\frac{dm}{dt}$
2.00	3.00	15.7	0.094	12.90	13.86	7	42.2						
2.50	3.00	15.9	0.092	13.16	14.04	7	42.9						
2.50	3.00	14.7	0.092	13.16	14.04	7	42.9						
3.25	3.00	14.5	0.091	13.92	14.55	4	43.8	28.816	74.81	11.05	11.19	101	3.328
3.25	3.00	14.2	0.097	13.66	14.65	7	43.0						
3.75	3.00	15.8	0.097	14.04	14.80	5	42.9						
3.75	3.00	14.8	0.101	14.04	14.93	6	42.9						
4.11	3.00	14.1	0.111	14.30	15.38	7	42.8						
4.50	3.00	14.8	0.111	14.93	15.50	4	42.3	32.587	99.60	15.49	15.12	98	3.241

See note on run.

Density (gm/cm^3)

Nickel coat = 6.68 Copper coat = 8.39

RUN 7 BED EXPANSION = 10%

Time (hr)	Current (Amps.)	Potential (volts)	Flow Rate (L/min)	S.B.V. (cm^3)	E.B.V. (cm^3)	% Bed Exp.	Sol. Temp (°C)	Total Mass (g)	% Metal coat	Total Theor. Metal Dep. (gm)	Total Actual Metal Dep. (gm)	Cathode Eff. (%)	$\frac{dm}{dt}$
0.00	1.50	10.0	0.070	10.34	11.48	11	24.0	18.005	3.06	0.00	0.00		
0.50	1.50	7.8	0.057	10.21	11.35	11	27.5						
1.00	1.50	7.1	0.055	10.21	11.35	11	28.5	19.449	11.30	1.77	1.43	81	1.444
1.00	1.50	7.7	0.062	10.08	11.10	10	28.5						
2.00	1.50	6.8	0.056	10.72	11.35	6	29.5						
2.00	1.50	7.4	0.081	10.72	11.80	10	29.0						
2.75	1.50	7.4	0.074	11.10	11.86	7	29.0						
2.75	1.50	7.5	0.086	10.97	12.05	10	29.0						
3.75	1.50	7.2	0.081	10.97	12.36	12	29.5	23.539	40.57	5.66	6.25	94	1.475
3.75	1.50	7.0	0.110	11.35	12.49	10	28.0						
4.75	1.50	7.2	0.106	11.98	12.87	8	29.5						
4.75	1.50	6.9	0.141	11.98	13.12	10	29.0						
5.75	1.50	6.6	0.134	11.98	13.63	14	29.0						
5.75	1.50	7.3	0.119	11.98	13.12	10	29.0						
7.00	1.50	7.3	0.110	12.74	13.76	8	29.5	28.891	75.80	12.44	11.92	96	1.555

RUN 7 (Cont.)

Time (hr)	Current (Amps.)	Potential (volts)	Flow Rate (L/min)	S.B.V. (cm^3)	E.B.V. (cm^3)	% Bed Exp.	Sol. Temp (°C)	Total Mass (gm)	% Metal coat	Total Theor. Metal Dep. (gm)	Total Actual Metal Dep. (gm)	Cathode Eff. (%)	$\frac{dm}{dt}$
7.00	1.50	7.8	0.174	12.74	14.02	10	28.0						
8.00	1.50	7.6	0.172	13.00	14.51	12	30.0						
8.00	1.50	7.4	0.160	13.00	14.51	12	30.0						
8.45	1.50	7.5	0.155	13.12	14.64	11	30.5						
8.45	1.50	7.5	0.181	13.25	14.51	10	30.0						
9.50	1.50	7.5	0.153	13.38	14.65	10	30.5	31.660	98.16	16.88	15.14	90	1.437

Density (gm/cm^3)

Nickel coat = 5.38 Copper coat = 8.54

RUN 8 BED EXPANSION = 10%

Time (hr)	Current (Amps)	Potential (volts)	Flow Rate (L/min)	S.B.V. (cm^3)	E.B.V. (cm^3)	% Bed Exp.	Sol. Temp (°C)	Total Mass (gm)	% Metal coat	Total Theor. Metal Dep. (gm)	Total Actual Metal Dep. (gm)	Cathode Eff. (%)	$\frac{dm}{dt}$
0.00	1.50	15.0	0.111	11.51	12.65	10	24.0	18.000	6.79	0.00	0.00		
0.50	1.50	11.6	0.119	11.76	12.90	10	30.0						
0.50	1.50	11.6	0.120	11.76	12.90	10	30.0						
1.00	1.50	10.4	0.123	12.02	13.16	9	31.5	19.110	13.39	1.77	1.11	63	1.110
1.00	1.50	11.0	0.135	11.99	13.16	10	31.5						
1.75	1.50	10.4	0.150	12.14	13.41	10	32.0						
1.75	1.50	10.4	0.153	12.14	13.41	10	32.0						
2.50	1.50	11.6	0.184	12.27	13.54	10	32.5						
2.50	1.50	11.6	0.186	12.27	13.54	10	32.5						
3.25	1.50	11.6	0.191	12.52	13.79	10	33.5						
3.25	1.50	11.6	0.193	12.52	13.79	10	33.5						
3.75	1.50	10.0	0.194	12.65	14.04	11	32.5	23.374	41.88	6.66	5.75	86	1.433
3.75	1.50	11.0	0.194	12.52	13.79	10	32.0						
4.50	1.50	10.4	0.206	12.65	14.17	12	32.5						
4.50	1.50	10.4	0.207	12.78	14.17	11	32.5						
5.25	1.50	9.4	0.212	12.90	14.30	11	32.0						
5.25	1.50	9.5	0.214	12.90	14.30	11	32.0						

RUN 8 (Cont.)

Time (hr)	Current (Amps.)	Potential (volts)	Flow Rate (L/min)	S.B.V. (cm^3)	E.B.V. (cm^3)	% Bed Exp.	Sol. Temp (°C)	Total Mass (gm)	% Metal coat	Total Theor. Metal Dep. (gm)	Total Actual Metal Dep. (gm)	Cathode Eff. (%)	$\frac{dm}{dt}$
6.00	1.50	10.8	0.212	12.78	14.30	12	32.5						
6.00	1.50	9.6	0.137	12.27	13.54	10	29.0						
7.00	1.50	9.8	0.146	12.90	14.30	11	32.5	29.327	77.13	12.44	11.62	93	1.618
7.00	1.50	8.5	0.144	12.52	13.79	10	32.0						
7.75	1.50	8.7	0.144	12.65	13.79	9	32.0						
7.75	1.50	8.4	0.154	12.52	13.92	11	32.0						
8.50	1.50	9.4	0.153	12.78	14.17	11	32.0						
8.50	1.50	8.2	0.155	12.78	14.02	10	32.0						
9.00	1.50	8.4	0.155	12.78	14.42	13	31.3						
9.00	1.50	8.4	0.157	12.78	14.02	10	31.3						
9.50	1.50	8.4	0.157	13.03	14.55	11	30.9	32.045	99.95	16.88	14.87	88	1.478

Density (gm/cm^3)

Nickel coat = 4.22 Copper coat = 8.97

RUN 9 BED EXPANSION = 10%

Time (hr)	Current (Amps)	Potential (volts)	Flow Rate (L/min)	S.B.V. (cm^3)	E.B.V. (cm^3)	% Bed Exp.	Sol. Temp (°C)	Total Mass (gm)	% Metal Coat	Total Theor. Metal Dep. (gm)	Total Actual Metal Dep. (gm)	Cathode Eff. (%)	$\frac{dm}{dt}$
0.00	2.25	16.4	0.116	12.87	14.01	9	24.0	18.000	5.95	0.00	0.00		
0.50	2.25	11.8	0.125	13.25	14.51	10	31.0						
0.50	2.25	11.8	0.129	13.25	14.51	10	31.0						
1.00	2.25	11.0	0.144	13.50	14.77	9	33.5	20.222	19.02	2.66	2.22	83	2.222
1.00	2.25	11.8	0.144	13.38	14.51	9	32.0						
1.50	2.25	11.2	0.155	13.50	14.77	9	34.0						
1.50	2.25	11.2	0.157	13.38	15.15	13	33.5						
2.00	2.25	10.5	0.162	13.88	15.02	9	34.0						
2.00	2.25	10.8	0.171	13.88	15.27	10	33.5						
2.75	2.25	12.3	0.191	14.14	15.53	10	34.5	24.779	46.60	7.33	6.86	94	2.465
2.75	2.25	12.4	0.175	13.88	15.27	10	33.0						
3.50	2.25	12.3	0.179	14.51	15.79	9	34.5						
3.50	2.25	12.3	0.184	14.39	15.79	10	34.5						
4.00	2.25	12.2	0.191	14.77	16.05	9	35.0	27.936	64.71	10.66	9.96	93	2.484

RUN 9 (Cont.)

Time (hr)	Current (Amps.)	Potential (volts)	Flow Rate (L/min)	S.B.V. (cm^3)	E.B.V. (cm^3)	% Bed Exp.	Sol. Temp (°C)	Total Mass (gm)	% Metal coat	Total Theor. Metal Dep. (gm)	Total Actual Metal Dep. (gm)	Cathode Eff. (%)	$\frac{dm}{dt}$
4.00	2.25	12.4	0.171	14.14	15.53	10	33.5						
4.75	2.25	13.8	0.178	14.64	16.05	10	35.0						
4.75	2.25	13.8	0.181	14.51	16.05	10	35.0						
5.65	2.25	13.5	0.186	15.27	16.57	9	35.0						
5.65	2.25	11.5	0.194	15.27	16.57	9	35.0						
6.25	2.25	12.7	0.205	15.27	16.83	10	35.0	33.670	100.70	16.66	15.88	95	2.507

Density (gm/cm^3)

Nickel coat = 5.10 Copper coat 8.59

RUN 10 BED EXPANSION = 10%

Time (hr)	Current (Amps.)	Potential (volts)	Flow Rate (L/min)	S.B.V. (cm^3)	E.B.V. (cm^3)	% Bed Exp.	Sol. Temp (°C)	Total Mass (gm)	% Metal ccat	Total Theor. Metal Dep. (gm)	Total Actual Metal Dep. (gm)	Cathode Eff. (%)	$\frac{dm}{dt}$
0.00	2.25	14.0	0.125	11.22	12.24	9	24.0	18.000	5.80	0.00	0.00		
0.50	2.25	11.5	0.124	11.98	12.87	8	32.0						
0.50	2.25	11.5	0.129	11.98	13.19	10	32.0						
1.25	2.25	11.0	0.137	12.24	13.38	9	34.0	21.162	24.38	3.33	3.16	95	2.530
1.25	2.25	11.8	0.141	11.98	13.18	10	33.0						
2.00	2.25	11.0	0.150	12.49	13.50	8	34.0						
2.00	2.25	11.3	0.184	12.49	13.76	10	33.5						
2.75	2.25	10.2	0.183	12.87	14.13	10	34.0	24.933	48.05	7.33	7.10	97	2.521
2.75	2.25	12.2	0.186	12.74	13.88	9	33.5						
3.50	2.25	11.1	0.185	13.25	14.26	8	35.0						
3.50	2.25	11.6	0.198	13.25	14.51	10	35.0						
4.00	2.25	11.4	0.213	13.50	14.7[illegible]	9	34.5	27.585	65.84	10.66	9.96	93	2.396

RUN 10 (Cont.)

Time (hr)	Current (Amps.)	Potential (volts)	Flow Rate (L/min)	S.B.V. (cm^3)	E.B.V. (cm^3)	% Bed Exp.	Sol. Temp (°C)	Total Mass (gm)	% Metal coat	Total Theor. Metal Dep. (gm)	Total Actual Metal Dep. (gm)	Cathode Eff. (%)	$\frac{dm}{dt}$
4.00	2.25	11.6	0.169	13.25	14.51	10	33.5						
4.75	2.25	11.0	0.181	13.88	15.02	9	34.0						
4.75	2.25	10.9	0.203	14.01	15.27	9	34.0						
5.75	2.25	11.1	0.212	14.26	15.79	10	34.0						
5.75	2.25	11.1	0.213	14.26	15.79	10	34.0						
6.25	2.25	10.5	0.214	14.51	16.05	10	34.0	33.566	103.33	16.66	16.07	96	2.490

Density (gm/cm^3)

Nickel coat = 8.03 Copper coat = 8.53

RUN 11 BED EXPANSION = 10%

Time (hr)	Current (Amps.)	Potential (volts)	Flow Rate (L/min)	S.B.V. (cm^3)	E.B.V. (cm^3)	% Bed Exp.	Sol. Temp (°C)	Total Mass (gm)	% Metal coat	Total Theor. Metal Dep. (gm)	Total Actual Metal Dep. (gm)	Cathod Eff. (%)	$\frac{dm}{dt}$
0.00	3.00	16.8	0.148	13.25	14.51	10	26.0	18.001	5.27	0.00	0.00		
0.50	3.00	11.5	0.161	13.76	15.27	11	33.5	19.479	13.91	1.77	1.47	83	2.957
0.50	3.00	12.0	0.151	13.50	14.64	8	31.0						
1.00	3.00	11.8	0.154	13.63	15.02	10	35.5						
1.00	3.00	11.6	0.155	13.50	15.02	11	35.5						
1.50	3.00	11.8	0.160	14.01	15.27	9	36.5						
1.50	3.00	12.2	0.171	14.01	15.40	10	36.5						
2.00	3.00	15.00	0.176	14.39	15.79	10	37.5	24.667	45.29	7.11	6.78	95	3.333
2.00	3.00	12.4	0.174	14.26	15.53	9	31.0						
2.625	3.00	14.2	0.175	14.51	15.92	10	36.0						
2.625	3.00	13.4	0.172	14.51	15.53	7	36.0						
3.25	3.00	15.6	0.175	15.02	16.31	9	39.0	28.644	70.18	11.55	10.91	94	3.274
3.25	3.00	10.4	0.188	14.64	16.05	10	36.0						
3.875	3.00	12.8	0.185	15.27	16.83	10	37.0						
3.875	3.00	12.8	0.193	15.27	16.96	11	37.0						
4.50	3.00	14.7	0.191	15.53	17.22	11	37.5	32.675	95.58	16.00	15.06	94	3.261

Density (gm/cm^3)

Nickel coat = 6.15 Copper coat = 8.47

RUN 12 BED EXPANSION = 10%

Time (hr)	Current (Amps.)	Potential (volts)	Flow Rate (L/min)	S.B.V. (cm^3)	E.B.V. (cm^3)	% Bed Exp.	Sol. Temp (°C)	Total Mass (gm)	% Metal coat	Total Theor. Metal Dep. (gm)	Total Actual Metal Dep. (gm)	Cathode Eff. (%)	$\frac{dm}{dt}$
0.00	3.00	14.8	0.082	12.24	13.50	10	25.0	18.003	5.29	0.00	0.00		
0.50	3.00	13.3	0.085	13.38	14.01	5	34.0	19.362	13.25	1.77	1.35	76	2.718
0.50	3.00	14.9	0.160	13.25	14.64	10	29.0						
1.00	3.00	14.3	0.169	13.63	15.02	10	35.0						
1.00	3.00	14.3	0.169	13.50	15.02	11	35.0						
1.50	3.00	13.8	0.172	13.88	15.27	10	37.0						
1.50	3.00	14.2	0.175	14.01	15.27	9	36.2						
2.00	3.00	13.7	0.175	14.01	15.53	11	37.5	24.317	44.22	7.11	6.55	92	3.157
2.00	3.00	14.2	0.166	13.63	15.02	10	33.0						
2.63	3.00	13.5	0.169	14.39	15.79	10	37.2						
2.63	3.00	13.5	0.168	14.26	15.79	10	37.0						
3.25	3.00	12.6	0.172	14.77	16.05	9	38.0	28.286	69.89	11.55	10.73	93	3.164
3.25	3.00	12.8	0.184	14.51	16.05	10	33.0						
3.85	3.00	12.5	0.186	14.77	16.31	11	37.5						
3.85	3.00	13.1	0.188	14.77	16.31	11	37.0						
4.45	3.00	13.3	0.188	15.02	16.70	11	38.0	32.219	96.20	15.82	14.89	94	3.194

Density (gm/cm^3)

Nickel coat = 5.23 Copper coat = 8.48

RUN 13 BED EXPANSION = 15%

Time (hr)	Current (Amps.)	Potential (volts)	Flow Rate (L/min)	S.B.V. (cm^3)	E.B.V. (cm^3)	% Bed Exp.	Sol. Temp (°C)	Total Mass (gm)	% Metal coat	Total Theor. Metal Dep. (gm)	Total Actual Metal Dep. (gm)	Cathode Eff. (%)	$\frac{dm}{dt}$
0.00	1.50	12.5	0.181	11.73	13.50	15	24.0	17.997	3.51	0.00	0.00		
0.50	1.50	10.8	0.220	11.73	13.63	16	26.0						
0.50	1.50	10.7	0.221	11.73	13.63	16	26.0						
1.00	1.50	10.7	0.228	11.48	13.76	20	27.0	19.846	14.12	1.77	1.84	104	1.849
1.00	1.50	10.9	0.198	11.10	12.74	15	27.0						
1.75	1.50	10.6	0.206	11.22	13.00	16	28.5						
1.75	1.50	10.2	0.209	11.22	13.00	16	28.5						
2.50	1.50	10.2	0.217	11.48	13.25	15	28.5						
2.50	1.50	10.2	0.219	11.48	13.25	15	28.5						
3.25	1.50	10.6	0.228	11.60	13.36	15	29.0						
3.25	1.50	10.4	0.228	11.60	13.36	15	29.0						
3.75	1.50	10.2	0.231	11.73	13.50	15	29.0	23.788	39.48	6.66	6.12	92	1.544
3.75	1.50	10.0	0.214	11.48	13.25	15	28.5						
4.50	1.50	9.9	0.228	11.73	13.50	15	29.0						
4.50	1.50	10.0	0.228	11.73	13.50	15	29.0						
5.25	1.50	10.0	0.236	11.98	13.76	15	29.5						
5.25	1.50	10.0	0.239	11.98	13.76	15	29.5						

RUN 13 (Cont.)

Time (hr)	Current (Amps.)	Potential (volts)	Flow Rate (L/min)	S.B.V. (cm)	E.B.V. (cm)	% Bed Exp.	Sol. Temp (°C)	Total mass (gm)	% Metal coat	Total Theor. Metal Dep. (gm)	Total Actual Metal Dep. (gm)	Cathode Eff. (%)	$\frac{dm}{dt}$
6.00	1.50	10.0	0.254	12.11	14.01	16	30.0						
6.00	1.50	10.0	0.258	11.98	14.01	17	30.0						
6.50	1.50	10.0	0.263	12.24	14.14	15	30.0						
6.50	1.50	10.0	0.261	12.24	14.01	15	30.0						
7.00	1.50	10.0	0.266	12.36	14.14	15	30.0	29.093	72.00	12.44	11.56	93	1.585
7.00	1.50	9.7	0.254	12.11	14.01	16	30.0						
7.75	1.50	8.4	0.254	12.11	14.39	18	29.1						
7.75	1.50	8.8	0.235	12.11	13.88	14	28.5						
8.50	1.50	8.4	0.232	12.49	14.39	15	28.9						
8.50	1.50	8.4	0.235	12.49	14.39	15	28.8						
9.00	1.50	8.4	0.232	12.62	14.39	14	28.9						
9.00	1.50	8.5	0.235	12.62	14.64	16	28.9						
9.50	1.50	8.5	0.232	12.62	14.64	16	28.9	32.760	96.12	16.88	15.44	91	1.554

Density (gm/cm^3)

Nickel coat = 7.30 Copper coat = 8.81

RUN 14 BED EXPANSION = 15%

Time (hr)	Current (Amps.)	Potential (volts)	Flow Rate (L/min)	S.B.V. (cm^3)	E.B.V. (cm^3)	% Bed Exp.	Sol. Temp (°C)	Total Mass (gm)	% Metal coat	Total Theor. Metal Dep. (gm)	Total Actual Metal Dep. (gm)	Cathode Eff. (%)	$\frac{dm}{dt}$
0.00	1.50	12.6	0.118	12.78	14.02	10	23.0	18.000	6.10	0.00	0.00		
0.50	1.50	9.8	0.137	13.28	14.42	9	27.0						
0.50	1.50	9.6	0.196	13.28	15.31	15	27.0						
1.00	1.50	10.8	0.214	13.54	15.56	15	29.0	19.677	15.96	1.77	1.67	94	1.677
1.00	1.50	11.2	0.203	13.03	15.06	15	29.0						
1.75	1.50	11.4	0.228	13.28	15.31	15	29.5						
1.75	1.50	11.4	0.232	13.28	15.31	15	29.5						
2.50	1.50	11.4	0.241	13.66	15.69	15	30.0						
2.50	1.50	11.6	0.235	13.66	15.69	15	30.0						
3.00	1.50	12.0	0.236	13.92	15.94	14	30.5						
3.00	1.50	11.9	0.235	13.92	15.94	14	30.5						
3.75	1.50	12.4	0.242	14.04	16.07	14	31.0	23.944	44.87	6.66	6.38	96	1.585
3.75	1.50	9.0	0.220	13.79	15.82	15	30.5						
4.50	1.50	9.7	0.220	13.92	15.94	14	29.8						
4.50	1.50	9.4	0.227	13.92	15.94	14	29.8						
5.25	1.50	9.0	0.221	14.17	16.20	14	29.9						
5.25	1.50	9.1	0.224	14.17	16.20	14	29.9						

RUN 14 (Cont.)

Time (hr)	Current (Amps.)	Potential (volts)	Flow Rate (L/min)	S.B.V. (cm^3)	E.B.V. (cm^3)	% Bed Exp.	Sol. Temp (°C)	Total Mass (gm)	% Metal coat	Total Theor. Metal Dep. (gm)	Total Actual Metal Dep. (gm)	Cathode Eff. (%)	$\frac{dm}{dt}$
6.00	1.50	9.9	0.221	14.30	16.20	13	30.0						
6.00	1.50	9.9	0.230	14.30	16.45	15	30.0						
7.00	1.50	9.9	0.231	14.55	16.58	14	29.8	28.359	73.07	12.44	10.93	88	1.479
7.00	1.50	10.1	0.238	14.30	16.45	15	29.8						
7.75	1.50	10.1	0.232	14.30	16.45	15	29.8						
7.75	1.50	10.1	0.236	14.30	16.45	15	29.8						
8.50	1.50	10.4	0.231	14.80	16.58	12	30.0						
8.50	1.50	10.4	0.263	14.80	17.09	15	30.0						
9.00	1.50	12.1	0.266	14.93	17.34	16	30.0						
9.00	1.50	13.0	0.261	14.93	17.21	15	30.0						
9.50	1.50	13.4	0.258	14.80	17.21	16	31.0	33.141	103.29	16.88	15.80	94	1.593

Density (gm/cm^3)

Nickel coat = 6.46 Copper coat = 8.20

RUN 15 BED EXPANSION = 15%

Time (hr)	Current (Amps.)	Potential (volts)	Flow Rate (L/min)	S.B.V. (cm^3)	E.B.V. (cm^3)	% Bed Exp.	Sol. Temp (°C)	Total Mass (gm)	% Metal coat	Total Theor. Metal Dep. (gm)	Total Actual Metal Dep. (gm)	Cathode Eff. (%)	$\frac{dm}{dt}$
0.00	2.25	18.4	0.130	11.63	13.03	12	26.0	18.000	5.09	0.00	0.00		
0.08	2.25	16.8	0.133	11.63	13.54	16	26.2						
0.50	2.25	14.3	0.130	11.63	13.28	14	32.3						
0.50	2.25	14.5	0.172	11.63	13.54	16	32.3						
1.00	2.25	13.5	0.169	12.02	13.79	14	34.0	20.781	21.28	2.66	2.77	104	2.781
1.00	2.25	13.9	0.175	11.99	13.54	13	34.0						
1.75	2.25	13.3	0.175	12.14	14.04	15	34.5						
1.75	2.25	13.0	0.172	12.14	14.04	15	34.5						
2.25	2.25	13.1	0.169	12.40	14.04	13	35.6						
2.25	2.25	13.6	0.168	12.40	14.17	14	35.6						
2.75	2.25	14.0	0.168	12.65	14.17	12	36.0	24.635	46.30	7.33	6.92	94	2.413
2.75	2.25	13.4	0.188	12.52	14.42	15	36.0						
3.50	2.25	14.0	0.185	12.78	14.42	13	36.1						
3.50	2.25	13.6	0.207	12.78	14.68	15	36.1						
4.00	2.25	13.5	0.198	12.90	14.80	15	36.3	27.617	65.95	10.66	10.10	95	2.404

RUN 15 (Cont.)

Time (hr)	Current (Amps.)	Potential (volts)	Flow Rate (L/min)	S.B.V. (cm^3)	E.B.V. (cm^3)	% Bed Exp.	Sol. Temp (°C)	Total Mass (gm)	% Metal coat	Total Theor. Metal Dep. (gm)	Total Actual Metal Dep. (gm)	Cathode Eff. (%)	$\frac{dm}{dt}$
4.00	2.25	12.2	0.190	12.65	14.55	15	36.3						
4.75	2.25	14.7	0.188	13.16	15.31	1[illegible]	35.8						
4.75	2.25	13.2	0.197	13.16	15.18	15	35.8						
5.50	2.25	13.4	0.196	14.04	15.69	12	36.0						
5.50	2.25	14.4	0.251	14.04	16.20	15	36.0						
6.25	2.25	14.6	0.258	14.04	16.45	17	37.0	33.200	101.18	16.66	15.82	95	2.432

Density (gm/cm^3)

Nickel coat = 7.30 Copper coat = 8.27

RUN 16 BED EXPANSION = 15%

Time (hr)	Current (Amps.)	Potential (volts)	Flow Rate (L/min)	S.B.V. (cm^3)	E.B.V. (cm^3)	% Bed Exp.	Sol. Temp (°C)	Total Mass (gm)	% Metal coat	Total Theor. Metal Dep. (gm)	Total Actual Metal Dep. (gm)	Cathode Eff. (%)	$\frac{dm}{dt}$
0.00	2.25	18.3	0.155	11.76	13.28	13	24.0	18.000	5.80	0.00	0.00		
0.25	2.25	16.6	0.175	11.76	13.66	16	27.8						
0.50	2.25	14.0	0.171	12.40	14.17	14	31.7						
0.50	2.25	13.8	0.174	12.40	14.30	15	31.7						
1.00	2.25	13.2	0.171	12.40	14.17	14	33.9	20.351	19.62	2.66	2.34	88	2.351
1.00	2.25	13.2	0.179	12.27	14.17	15	33.9						
1.75	2.25	14.1	0.176	12.27	14.17	15	35.0						
1.75	2.25	14.6	0.198	12.27	14.30	17	35.0						
2.25	2.25	14.6	0.198	12.27	14.17	15	35.6						
2.25	2.25	14.6	0.198	12.27	14.17	15	35.6						
2.75	2.25	14.0	0.197	12.52	14.17	13	35.8	24.190	43.66	7.33	6.36	87	2.250
2.75	2.25	13.5	0.198	12.14	13.92	15	35.8						
3.50	2.25	13.3	0.197	12.78	14.17	11	35.0						
3.50	2.25	14.8	0.230	12.78	14.68	15	35.0						
4.00	2.25	16.2	0.228	12.78	14.80	16	36.0	27.230	64.29	10.66	9.66	91	2.307

RUN 16 (Cont.)

Time (hr)	Current (Amps.)	Potential (volts)	Flow Rate (L/min)	S.B.V. (cm^3)	E.B.V. (cm^3)	% Bed Exp.	Sol. Temp (°C)	Total Mass (gm)	% Metal coat	Total Theor. Metal Dep. (gm)	Total Actual Metal Dep. (gm)	Cathode Eff. (%)	$\frac{dm}{dt}$
4.00	2.25	15.7	0.228	12.27	14.17	15	36.0						
4.75	2.25	15.1	0.225	12.78	14.68	15	36.7						
4.75	2.25	14.6	0.228	12.78	14.68	15	36.7						
5.50	2.25	14.2	0.230	13.16	14.93	14	36.0						
5.50	2.25	14.4	0.242	13.16	15.12	15	36.0						
6.25	2.25	16.0	0.242	13.28	15.44	16	36.0	32.802	101.79	16.66	15.55	93	2.368

Density (gm/cm^3)

Nickel coat = 7.29 Copper coat = 8.25

RUN 17 BED EXPANSION = 15%

Time (hr)	Current (Amps.)	Potential (volts)	Flow Rate (L/min)	S.B.V. (cm^3)	E.B.V. (cm^3)	% Bed Exp.	Sol. Temp (°C)	Total Mass (gm)	% Metal coat	Total Theor. Metal Dep. (gm)	Total Actual Metal Dep. (gm)	Cathode Eff. (%)	$\frac{dm}{dt}$
0.00	3.00	20.0	0.14	1.48	13.00	14	23.0	18.000	5.50	0.00	0.00		
0.50	3.00	16.2	0.155	11.98	13.25	11	35.0	19.530	14.48	1.77	1.53	86	3.060
0.50	3.00	16.4	0.144	11.60	13.38	15	34.5						
1.00	3.00	15.6	0.158	11.98	13.63	14	38.5						
1.00	3.00	14.8	0.185	11.98	13.76	15	38.5						
1.50	3.00	15.2	0.191	12.11	13.88	14	39.0						
1.50	3.00	15.7	0.198	12.11	13.88	14	39.0						
2.00	3.00	16.3	0.206	12.24	14.14	15	39.0	24.599	45.54	7.11	6.75	95	3.299
2.00	3.00	16.2	0.185	12.11	13.88	14	30.0						
2.50	3.00	16.1	0.206	12.36	14.14	15	38.0						
2.50	3.00	14.7	0.227	12.49	14.23	14	38.0						
3.25	3.00	16.1	0.238	12.74	14.64	15	39.5	28.679	69.72	11.55	10.84	94	3.285
3.25	3.00	15.4	0.215	12.49	14.39	15	36.5						
3.75	3.00	15.5	0.228	12.74	14.64	15	39.0						
3.75	3.00	16.0	0.232	12.74	14.64	15	39.0						
4.50	3.00	16.6	0.242	13.25	15.40	16	40.0	32.780	96.36	16.00	15.14	95	3.284

Density (gm/cm^3)

Nickel coat = 6.06 Copper coat = 8.59

RUN 18 BED EXPANSION = 15%

Time (hr)	Current (Amps.)	Potential (volts)	Flow Rate (L/min)	S.B.V. (cm^3)	E.B.V. (cm^3)	% Bed Exp.	Sol. Temp (°C)	Total Mass (gm)	% Metal coat	Total Theor. Metal Dep. (gm)	Total Actual Metal Dep (gm)	Cathode Eff. (%)	$\frac{dm}{dt}$
0.00	2.50	18.5	0.221	13.01	14.99	15	23.0	18.000	5.52	0.00	0.00		
0.30	3.00	17.0	0.225	13.01	14.99	15	29.8						
0.50	3.00	16.0	0.228	13.24	15.24	15	35.5	19.196	12.48	1.60	1.18	7%	2.393
0.50	3.00	15.9	0.225	13.01	14.99	15	34.5						
1.00	3.00	15.8	0.228	12.52	14.64	17	39.0						
1.00	3.00	15.5	0.221	12.52	14.41	15	38.5						
1.50	3.00	16.0	0.228	12.65	14.64	16	40.0						
1.50	3.00	16.1	0.231	12.78	14.64	15	39.5						
2.00	3.00	16.1	0.228	12.40	14.41	16	41.5	23.163	37.65	6.93	5.39	78	2.581
2.00	2.00	14.0	0.228	12.26	14.06	15	30.0						
2.50	3.00	15.0	0.238	13.59	15.50	14	36.5						
2.50	3.00	15.0	0.249	13.59	15.64	15	36.0						
3.25	3.00	14.9	0.261	13.36	15.50	16	39.0	26.922	60.20	11.37	9.17	81	2.745
3.25	3.00	15.8	0.235	13.24	15.24	15	36.0						
4.00	3.00	18.0	0.253	13.59	15.64	15	37.0						
4.00	3.00	17.6	0.255	13.59	15.64	15	36.0						
4.50	3.00	17.3	0.271	13.83	15.90	15	40.0	30.556	83.73	15.82	12.98	82	2.790

Density (gm/cm^3)

Nickel coat = 6.00 Copper coat = 8.21

RUN 19 BED EXPANSION = 20%

Time (hr)	Current (Amps.)	Potential (volts)	Flow Rate (L/min)	S.B.V. (cm^3)	E.B.V. (cm^3)	% Bed Exp.	Sol. Temp (°C)	Total Mass (gm)	% Metal coat	Total Theor. Metal Dep. (gm)	Total Actual Metal Dep. (gm)	Cathode Eff. (%)	$\frac{dm}{dt}$
0.00	1.50	13.2	0.094	11.76	12.90	10	23.0	18.000	5.12	0.00	0.00		
0.33	1.50	12.8	0.175	11.76	13.98	19	26.8						
0.50	1.50	11.6	0.174	11.99	14.24	19	27.2						
0.50	1.50	12.0	0.198	11.99	14.36	20	27.5						
1.00	1.50	11.8	0.193	12.27	14.30	17	28.9	19.606	14.45	1.77	1.59	90	1.606
1.00	1.50	12.0	0.210	12.02	14.36	19	28.9						
1.75	1.50	11.1	0.213	12.14	14.49	19	29.2						
1.75	1.50	10.7	0.228	12.14	14.55	20	29.2						
2.67	1.50	10.6	0.228	12.14	14.62	20	30.0						
3.25	1.50	10.5	0.228	12.34	14.62	19	30.0						
3.25	1.50	10.6	0.245	12.34	14.80	20	30.0						
3.75	1.50	10.6	0.244	12.40	14.80	20	30.1	23.945	41.35	6.66	6.12	92	1.585
3.75	1.50	10.6	0.230	12.02	14.55	21	30.1						
4.50	1.50	10.9	0.228	12.34	14.72	19	30.2						
4.50	1.50	12.4	0.241	12.34	14.80	20	30.1						
5.25	1.50	11.5	0.239	12.52	15.18	21	31.0						
5.25	1.50	10.6	0.235	12.52	14.93	19	31.0						

RUN 19 (Cont.)

Time (hr)	Current (Amps.)	Potential (volts)	Flow Rate (L/min)	S.B.V. (cm^3)	E.B.V. (cm^3)	% Bed Exp.	Sol. Temp (°C)	Total Mass (gm)	% Metal coat	Total Theor. Metal Dep. (gm)	Total Actual Metal Dep. (gm)	Cathode Eff. (%)	$\frac{dm}{dt}$
6.00	1.50	10.6	0.232	12.72	15.12	19	31.0						
6.00	1.50	10.3	0.239	12.72	15.31	20	31.0						
6.50	1.50	10.3	0.239	12.90	15.31	19	31.0						
6.50	1.50	10.3	0.245	12.90	15.44	20	31.0						
7.00	1.50	10.4	0.245	12.90	15.50	20	31.0	28.972	73.26	12.44	11.37	91	1.567
7.00	1.50	10.2	0.249	12.27	14.68	20	31.0						
7.75	1.50	10.3	0.251	12.65	15.12	20	31.0						
8.50	1.50	9.0	0.253	12.78	15.18	19	31.0						
8.50	1.50	10.3	0.260	12.78	15.44	21	31.0						
9.00	1.50	10.0	0.258	13.16	15.38	17	31.1						
9.00	1.50	10.1	0.290	13.16	15.69	19	31.1						
9.50	1.50	10.3	0.290	13.28	15.88	20	31.1	31.997	98.96	16.88	15.03	89	1.473

Density (gm/cm^3)

Nickel coat = 6.49 Copper coat = 8.36

RUN 20 BED EXPANSION = 20%

Time (hr)	Current (Amps.)	Potential (volts)	Flow Rate (L/min)	S.B.V. (cm^3)	E.B.V. (cm^3)	% Bed Exp.	Sol. Temp (°C)	Total Mass (gm)	% Metal coat	Total Theor. Metal Dep. (gm)	Total Actual Metal Dep. (gm)	Cathode Eff. (%)	$\frac{dm}{dt}$
0.00	1.50	16.1	0.178	12.14	13.86	14	23.1	18.000	5.43	0.00	0.00		
0.25	1.50	14.4	0.220	12.14	14.42	19	26.6						
0.50	1.50	12.7	0.220	12.14	14.55	20	28.3						
1.00	1.50	11.9	0.225	12.27	14.75	20	29.8	19.703	15.43	1.77	1.70	96	1.703
1.00	1.50	11.0	0.203	11.76	14.11	20	29.8						
1.75	1.50	11.3	0.203	11.99	14.04	17	30.1						
1.75	1.50	11.7	0.220	11.99	14.36	20	30.1						
2.50	1.50	11.7	0.220	11.63	14.17	21	30.8						
2.50	1.50	11.1	0.220	11.63	14.17	21	30.8						
3.25	1.50	11.1	0.224	11.99	14.04	17	30.8						
3.25	1.50	11.6	0.258	11.99	14.36	20	30.8						
3.75	1.50	12.0	0.261	12.02	14.62	21	30.0	23.471	19.01	4.88	5.65	116	1.459
3.75	1.50	11.1	0.235	11.51	13.79	20	30.0						
4.50	1.50	11.6	0.232	11.51	13.92	20	31.0						
4.50	1.50	11.4	0.231	11.51	13.79	20	31.0						
5.33	1.50	11.3	0.231	11.63	13.92	20	31.5						
5.33	1.50	11.3	0.231	11.63	13.92	20	31.5						

RUN 20 (Cont.)

Time (hr)	Current (Amps.)	Potential (volts)	Flow Rate (L/min)	S.B.V. (cm^3)	E.B.V. (cm^3)	% Bed Exp.	Sol. Temp (°C)	Total Mass (gm)	% Metal coat	Total Theor. Metal Dep. (gm)	Total Actual Metal Dep. (gm)	Cathode Eff. (%)	$\frac{dm}{dt}$
5.75	1.50	11.3	0.231	11.76	13.92	19	31.7						
5.75	1.50	11.0	0.238	11.76	13.92	19	31.7						
6.30	1.50	11.5	0.238	12.02	14.11	17	31.9						
6.30	1.50	12.1	0.245	12.02	14.42	20	31.9						
7.00	1.50	10.3	0.245	12.27	14.42	18	32.0	28.365	72.71	10.66	11.01	103	1.480
7.00	1.50	10.6	0.248	11.99	14.42	20	32.0						
7.75	1.50	11.5	0.249	12.02	14.42	20	31.3						
7.75	1.50	9.6	0.257	12.02	14.42	20	31.3						
8.50	1.50	9.1	0.257	12.52	14.80	18	31.2						
8.50	1.50	9.2	0.267	12.52	14.93	19	31.2						
9.00	1.50	9.4	0.267	12.78	15.12	19	31.3						
9.00	1.50	9.2	0.276	12.78	15.31	20	31.1						
9.50	1.50	9.1	0.276	12.78	15.44	21	31.0	32.601	101.62	15.11	15.50	103	1.536

Density (gm/cm^3)

Nickel coat = 6.60 Copper coat = 8.37

RUN 21 BED EXPANSION = 20%

Time (hr)	Current (Amps.)	Potential (volts)	Flow Rate (L/min)	S.B.V. (cm^3)	E.B.V. (cm^3)	% Bed Exp.	Sol. Temp (°C)	Total Mass (gm)	% Metal coat	Total Theor. Metal Dep. (gm)	Total Actual Metal Dep. (gm)	Cathode Eff. (%)	$\frac{dm}{dt}$
0.00	2.25	17.8	0.161	12.02	13.66	13	23.0	18.000	5.03	0.00	0.00		
0.25	2.25	14.1	0.210	12.02	14.30	19	27.2						
0.50	2.25	13.4	0.217	12.02	14.36	19	30.1						
0.50	2.25	14.2	0.219	12.02	14.42	20	30.1						
1.00	2.25	13.5	0.217	12.02	14.36	19	33.2	20.139	17.51	2.66	2.13	80	2.139
1.00	2.25	13.0	0.217	11.76	14.14	20	33.2						
1.75	2.25	12.8	0.217	11.57	14.04	22	34.0						
1.75	2.25	13.3	0.231	11.57	13.92	21	34.0						
2.25	2.25	15.7	0.231	11.76	13.92	19	35.2						
2.25	2.25	14.1	0.221	11.76	14.04	20	35.2						
2.75	2.25	14.3	0.221	11.76	14.04	20	35.5	23.540	39.68	7.33	5.82	79	2.014
2.75	2.25	14.0	0.220	11.51	13.79	20	35.5						
3.50	2.25	14.3	0.225	11.76	13.98	19	36.2						
3.50	2.25	14.2	0.235	11.76	14.11	20	36.2						

RUN 21 (Cont.)

Time (hr)	Current (Amps.)	Potential (volts)	Flow Rate (L/min)	S.B.V. (cm^3)	E.B.V. (cm^3)	% Bed Exp.	Sol. Temp (°C)	Total Mass (gm)	% Metal coat	Total Theor. Metal Dep. (gm)	Total Actual Metal Dep. (gm)	Cathode Eff. (%)	$\frac{dm}{dt}$
4.00	2.25	13.8	0.238	11.99	14.24	19	36.5	26.805	60.77	10.66	9.27	87	2.201
4.00	2.25	13.8	0.262	11.76	14.11	20	36.5						
4.75	2.25	13.7	0.263	12.14	14.80	22	35.2						
4.75	2.25	13.6	0.253	12.14	14.55	20	35.2						
5.50	2.25	13.3	0.253	12.14	14.55	20	35.8						
5.50	2.25	15.2	0.258	12.14	14.55	20	35.8						
6.25	2.25	14.8	0.257	12.27	14.93	22	36.9	32.193	96.17	16.66	14.91	90	2.270

Density (gm/cm^3)

Nickel coat = 6.35 Copper coat = 8.68

RUN 22 BED EXPANSION - 20%

Time (hr)	Current (Amps.)	Potential (volts)	Flow Rate (L/min)	S.B.V. (cm^3)	E.B.V. (cm^3)	% Bed Exp.	Sol. Temp (°C)	Total Mass (gm)	% Metal coat	Total Theor. Metal Dep. (gm)	Total Actual Metal Dep. (gm)	Cathode Eff. (%)	$\frac{dm}{dt}$
0.00	1.50	13.2	0.088	12.27	13.60	11	22.4	18.000	5.49	0.00	0.00		
0.12	2.25	17.0	0.108	12.27	14.68	20	27.1						
0.50	2.25	15.8	0.185	12.27	14.68	20	31.0						
1.00	2.25	15.7	0.183	12.02	14.42	20	35.0		20.01	2.56	2.47	97	2.482
1.00	2.25	14.8	0.198	12.02	14.42	20	35.0						
1.50	2.25	15.4	0.201	12.14	14.17	17	35.1						
1.50	2.25	15.8	0.244	12.14	14.55	20	35.1						
2.25	2.25	15.8	0.254	12.27	14.80	21	36.2						
2.25	2.25	16.3	0.261	12.27	14.75	20	36.2						
2.75	2.25	17.3	0.274	12.40	15.06	21	37.4	24.886	47.56	7.22	7.08	98	2.504
2.75	2.25	15.4	0.253	12.14	14.55	20	37.4						
3.50	2.25	14.2	0.260	12.52	14.93	19	36.2						
3.50	2.25	14.3	0.274	12.52	15.00	20	36.2						

RUN 22 (Cont.)

Time (hr)	Current (Amps.)	Potential (volts)	Flow Rate (L/min)	S.B.V. (cm^2)	E.B.V. (cm^3)	% Bed Exp.	Sol. Temp (°C)	Total Mass (gm)	% Metal coat	Total Theor. Metal Dep. (gm)	Total Actual Metal Dep. (gm)	Cathode Eff. (%)	$\frac{dm}{dt}$
4.00	2.25	14.7	0.277	12.78	15.31	20	35.8	27.827	66.18	10.56	10.14	96	2.456
4.00	2.25	14.0	0.270	12.52	15.06	20	35.8						
4.50	2.25	14.3	0.270	12.78	15.31	20	35.5						
4.50	2.25	14.3	0.270	12.78	15.31	20	35.5						
5.25	2.25	14.4	0.270	13.03	15.69	20	35.3						
5.25	2.25	14.1	0.271	13.03	15.69	20	35.3						
5.75	2.25	14.0	0.285	13.28	15.88	20	35.7						
5.75	2.25	14.0	0.290	13.28	15.94	20	35.7						
6.25	2.25	14.2	0.290	13.54	16.20	20	36.0	33.230	99.97	16.56	15.67	95	2.436

Density (gm/cm^3)

Nickel coat = 6.38 Copper coat = 8.63

RUN 23 BED EXPANSION = 20%

Time (hr)	Current (Amps.)	Potential (volts)	Flow Rate (L/min)	S.B.V. (cm^3)	E.B.V. (cm^3)	% Bed Exp.	Sol. Temp (°C)	Total mass (gm)	% Metal coat	Total Theor. Metal Dep. (gm)	Total Actual Metal Dep. (gm)	Cathode Eff. (%)	$\frac{dm}{dt}$
0.00	1.50	14.8	0.148	12.02	13.48	12	22.0	18.000	5.31	0.00	0.00		
0.07	2.00	18.4	0.144	12.02	13.48	12	23.3						
0.11	2.30	18.4	0.141	12.02	13.48	12	24.6						
0.15	2.60	18.4	0.139	12.02	13.48	12	25.9						
0.20	2.80	18.4	0.138	12.02	13.48	12	27.2						
0.25	3.00	18.4	0.137	12.27	13.73	12	28.1						
0.33	2.50	18.4	0.228	12.27	14.17	15	30.1						
0.38	2.70	18.4	0.228	12.27	14.17	15	31.0						
0.50	2.70	18.4	0.244	12.27	14.42	18	32.3	19.468	13.93	1.46	1.47	100	2.937
0.50	2.70	18.4	0.254	12.02	14.49	20	32.3						
1.00	2.70	18.0	0.251	12.02	14.55	21	37.9						
1.00	2.80	18.4	0.248	12.02	14.42	20	37.9						
1.50	2.80	17.8	0.253	11.76	14.30	22	40.0						
1.50	3.00	17.4	0.249	11.76	14.04	20	40.0						

RUN 23 (Cont.)

Time (hr)	Current (Amps.)	Potential (volts)	Flow Rate (L/min)	S.B.V. (cm^3)	E.B.V. (cm^3)	% Bed Exp.	Sol. Temp (°C)	Total Mass (gm)	% Metal coat	Total Theor. Metal Dep. (gm)	Total Actual Metal Dep. (gm)	Cathode Eff. (%)	$\frac{dm}{dt}$
2.00	3.00	17.5	0.254	11.99	14.17	18	41.2	23.741	39.66	6.50	5.83	90	2.870
2.00	3.00	16.8	0.251	11.76	14.04	20	41.2						
2.50	3.00	17.6	0.251	12.02	14.42	20	41.1						
2.50	3.00	17.5	0.257	12.02	14.42	20	41.1						
3.25	3.00	17.4	0.260	12.27	14.30	17	41.7	27.681	64.76	10.95	9.97	91	2.978
3.25	3.00	16.0	0.219	12.14	14.55	20	41.7						
3.58	3.00	16.2	0.224	12.65	14.30	13	39.2						
3.58	3.00	16.9	0.281	12.65	15.16	20	39.2						
4.17	3.00	15.7	0.284	13.03	15.69	20	40.1						
4.17	3.00	15.6	0.284	13.03	15.63	20	40.1						
4.50	3.00	16.2	0.288	13.16	15.82	20	40.0	32.099	93.80	15.39	14.62	95	3.133

Density (gm/cm^3)

Nickel coat = 6.77 Copper coat = 8.52

RUN 24 BED EXPANSION = 20%

Time (hr)	Current (Amps.)	Potential (volts)	Flow Rate (L/min)	S.B.V. (cm^3)	E.B.V. (cm^3)	% Bed Exp.	Sol. Temp (°C)	Total Mass (gm)	% Metal coat	Total Theor. Metal Dep. (gm)	Total Actual Metal Dep. (gm)	Cathode Eff. (%)	$\frac{dm}{dt}$
0.00	1.5	15.9	0.149	12.02	13.60	13	22.5	18.000	4.94	0.00	0.00		
0.07	2.0	17.6	0.146	12.02	13.60	13	23.1						
0.10	2.2	17.2	0.144	12.02	13.60	13	24.0						
0.18	2.2	18.4	0.178	12.02	14.36	19	26.0						
0.25	2.5	17.7	0.178	12.02	14.36	19	27.5						
0.50	2.5	17.7	0.179	12.27	14.24	16	31.4	19.263	12.32	1.32	1.26	95	2.525
0.50	2.8	17.6	0.191	12.02	14.36	19	31.4						
0.75	3.00	17.8	0.238	12.02	14.36	19	35.9						
1.00	3.00	17.7	0.244	12.14	14.55	20	38.1						
1.00	3.00	17.7	0.249	12.14	14.55	20	38.1						
1.50	3.00	17.2	0.262	12.27	14.68	20	41.0						
1.50	3.00	17.1	0.268	12.27	14.68	20	41.0						
2.00	3.00	18.0	0.298	12.52	15.06	20	41.1	24.133	41.62	6.60	6.24	95	3.066
2.00	3.00	18.0	0.270	12.27	14.68	20	41.1						

RUN 24 (Cont.)

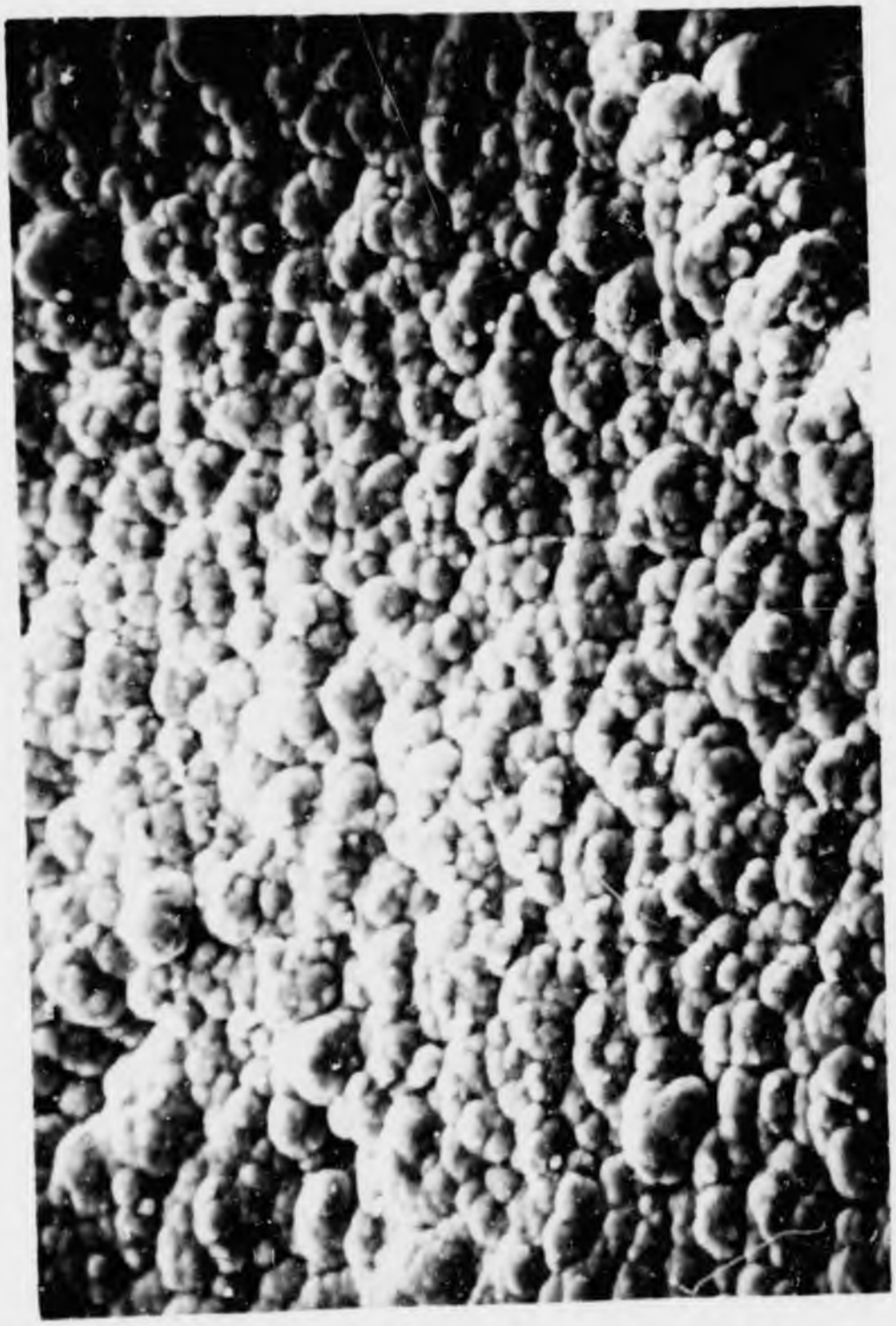
Time (hr)	Current (Amps.)	Potential (volts)	Flow Rate (L/min)	S.B.V. (cm^3)	E.B.V. (cm^3)	% Bed Exp.	Sol. Temp (°C)	Total Mass (gm)	% Metal coat	Total Theor. Metal Dep. (gm)	Total Actual Metal Dep. (gm)	Cathode Eff. (%)	$\frac{dm}{dt}$
2.50	3.00	16.7	0.281	12.40	14.93	20	40.5						
2.50	3.00	17.1	0.285	12.40	14.93	20	40.5						
2.83	3.00	17.3	0.287	14.46	14.93	20	41.1						
2.83	3.00	17.5	0.291	14.46	14.93	20	41.1						
3.25	3.00	17.3	0.288	12.65	15.06	19	41.2	27.886	65.13	11.04	10.15	92	3.042
3.25	3.00	17.7	0.288	12.40	14.93	20	41.2						
3.83	3.00	16.4	0.290	12.90	15.50	20	40.9						
3.83	3.00	16.6	0.290	12.90	15.44	20	40.9						
4.50	3.00	17.7	0.298	13.28	15.94	20	41.3	32.273	92.98	15.49	14.69	95	3.171

Density (gm/cm^3)

Nickel coat = 5.98 Copper coat = 8.32



Plate XXIV/1 Mod 2 General view of the particles.
(Mag. 120X)









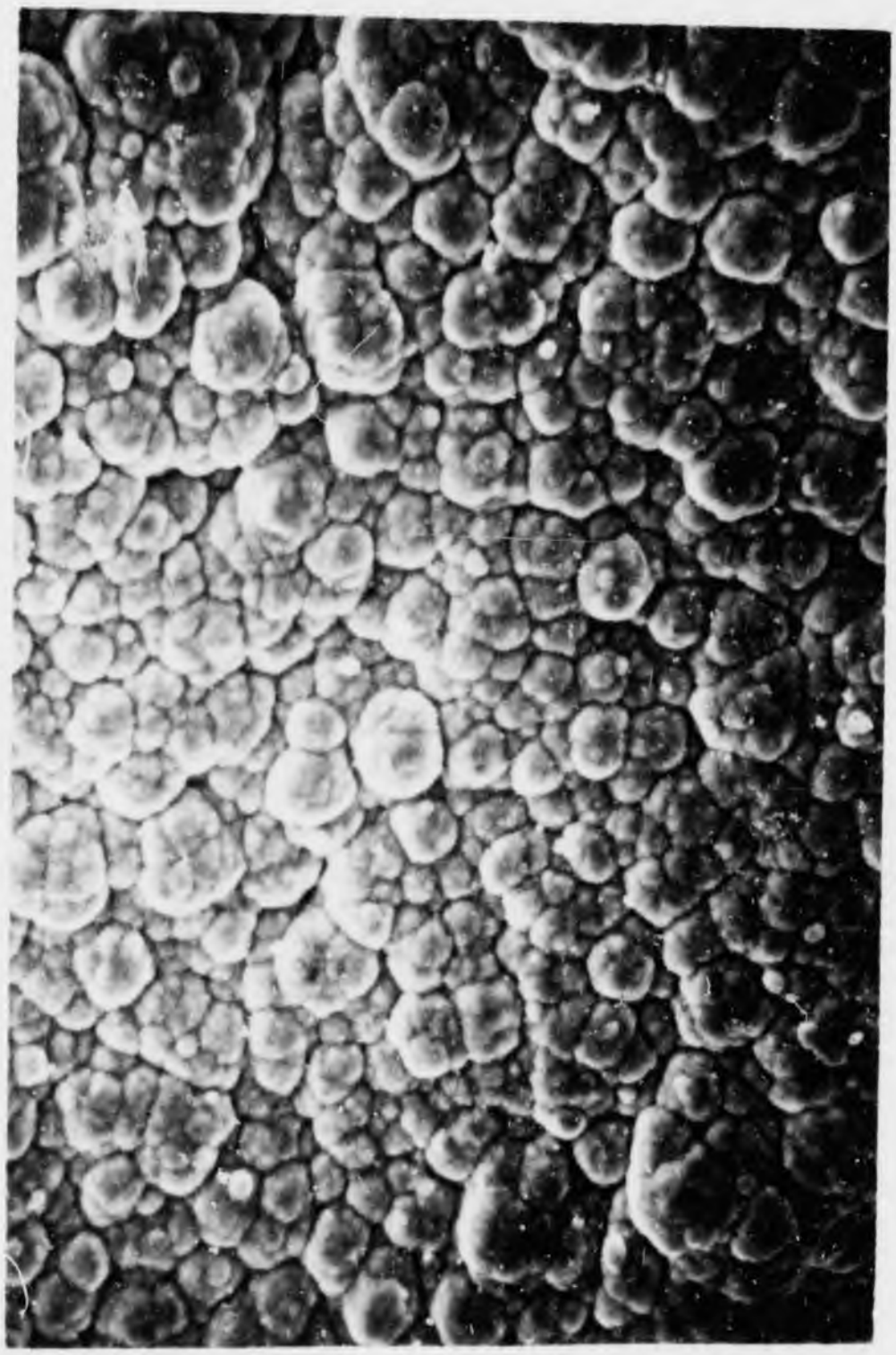
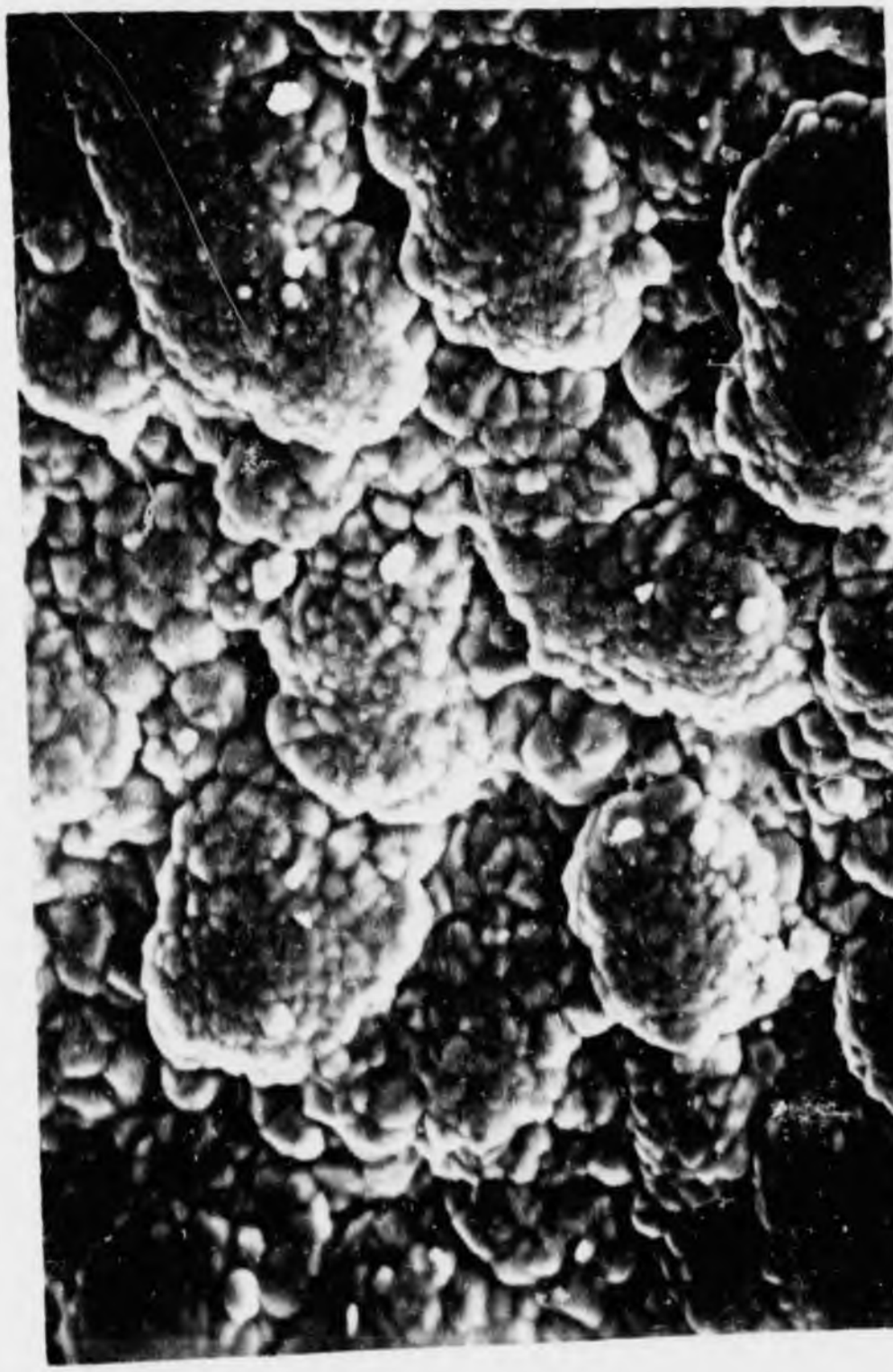




Plate 3B1212: Run 9 The roughest coat deposited on these particles. (Mag. 1200X)

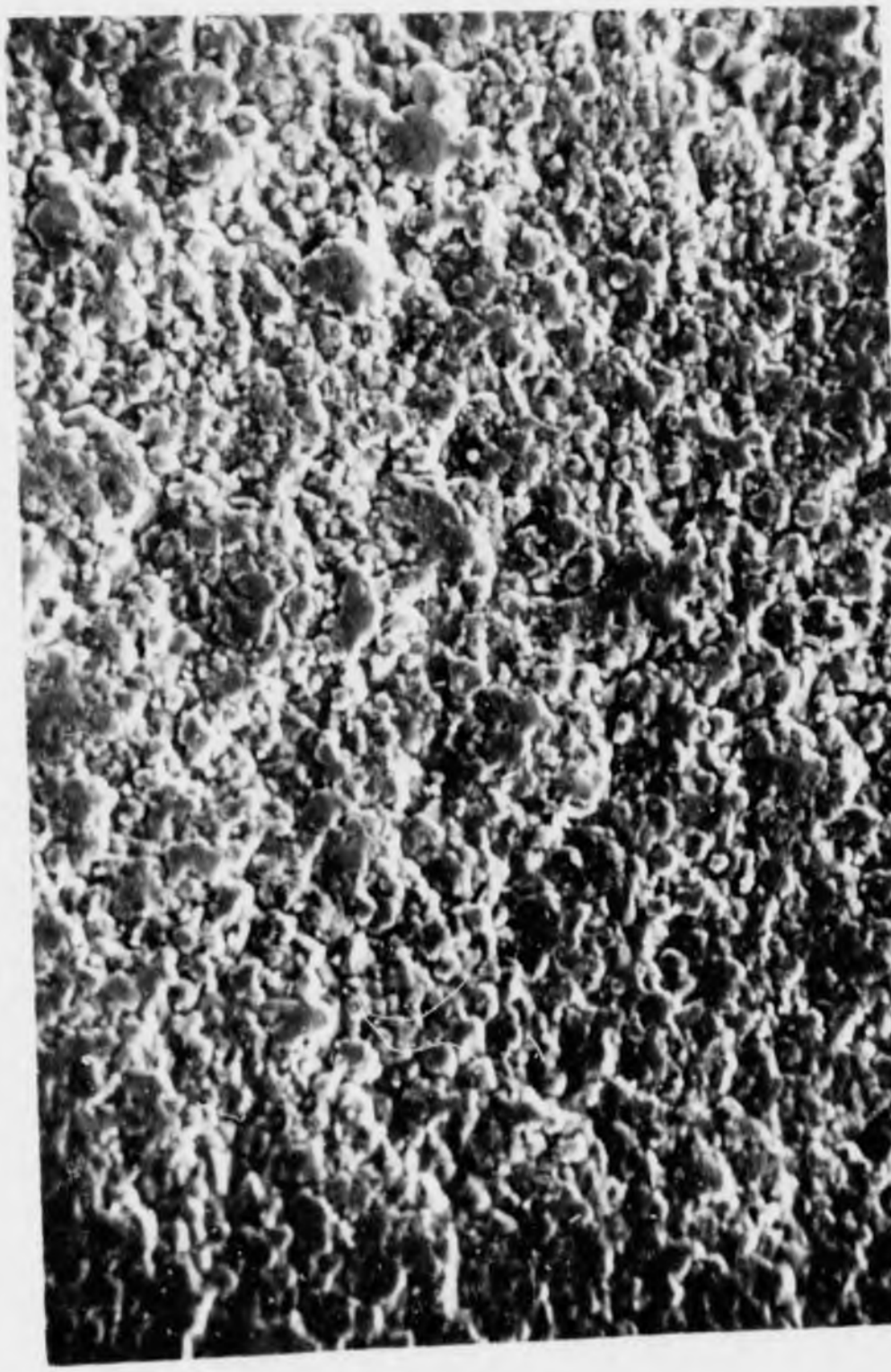






(Mag. 1200X)







(Mag. 1200X)

Author Dewar B I
Name of thesis A pulsating-fluidised bed system for the electroytic coating of diamond particles 1972

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