A STUDY OF TWO HIGH SPEED PROCESSES FOR THE PERMANENT RETENTION OF TRANSIENT IMAGES ON NON-SENSITIZED PAPER.

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Preface

The work described here was performed by the author while he was employed as a Research Assistant in the Mechanical Engineering Department of Loughborough University of Technology between October 1963 and July 1968. When he moved to Cambridge in 1968 the writing of this thesis was incomplete; this move and other domestic factors delayed its submission until February 1971. An attempt has been made to present the work against the changing background in the computer field over the whole period.

The approach throughout has been that of an Engineer who wants to make things work, and who believes that the justification for the presentation of this work lies in the potential of the results which were obtained.

Except where otherwise stated, the author was responsible for the work, its description and the opinions expressed.

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List of Symbols used in Section 7

A	Area	mm^2
C	Specific Heat	J/gK
D	Thermal Difusivity	mm^2/s
E	Energy Density	J/mm^2
e	Emissivity	
F	Heat Flux	W/mm^2
k	Thermal Conductivity	W/mmK
L	Latent heat	J/g
M	Mass	g
Q	Heat Quantity	J
r	Spot radius	mm
t	Time	s
V	Velocity	mm/s
W	Laser beam power	W
w	Density	g/mm^3
Y	Spot width	mm
Z	Thickness	mm
θ	Temperature	K

Subscripts

a	Ambient
d	Degradation
i	Ink
l	Laser
m	Melting
p	Paper

1.0 Summary

A study is made of the features required of a printer capable of producing a visible record of transient data. Particular attention is paid to the output requirements of digital electronic computers. A literature survey of high speed printers, both mechanical and non-mechanical, is given. Two feasibility studies are described, the first of a Xerographic printer and the second of a laser printer.

A description is given of experimental work in which optical information was printed Xerographically at speeds in excess of 5,000 lines per minute. The reasons for discontinuing this line of research are stated.

A proposed laser printer is then described together with the experimental work performed to determine the feasibility of the principal process involved. This process, the fusing of powdered ink onto paper, is also considered theoretically in terms of heat transfer.

An evaluation is made of the acceptibility of the images produced. The areas where further research is required to complete the study to the stage of operational printing are indicated.

2.0 Introduction

The production of a permanent visible record of digital information at high speeds is becoming increasingly important in the data processing, computing and communications fields. Many systems with high internal speeds have their effectiveness reduced by slow output printers. The upper limit of speed for mechanical printers appears to have been reached. Many non-mechanical printing methods have been investigated. Most have the disadvantages of using expensive materials and of producing printing of inferior contrast and stability.

2.1 Historical Survey of High Speed Random Image Transfer

One hundred and fifty years ago when long distance communication was by semaphor and computation was manual, the writing by hand of messages and numerical results was fast enough. When Babbage made his first mechanical computers in about 1820, he intended that the results should be printed automatically, but the printing mechanisms were not completed at that time. (2/1)*. One of the earliest high speed printers was that developed by a Mr. Callahan in 1867, possibly from earlier European machines, for use in the New York Stock Exchange. This "stock ticker" printed share and gold prices from telegraph signals. Edison patented his refined design of this printer early in 1868 (2/2). A revolving typewheel was used against which a hammer struck a paper tape when the required character was in position. The printer was fed by punched paper tape and not directly from the telegraph line. By September 1872 Edison was claiming

* References are listed in Section 12

speeds of 250 words per minute for his automatic telegraph (2/3). The printing however was probably limited to about 80 characters per minute (2/4). In spite of great activity in Europe and America in the development of high speed printers, particularly at the turn of the century, no dramatic advances in speed were made.

At the critical period on the New York Stock exchange in 1929 - 30, printers were limited to 275 characters per minute. These printers were replaced in September 1930 by new models capable of 500 characters per minute (2/5). By this time increasing use was being made of teletypewriters or teleprinters as they are now called. These could be used for message transmission using normal telegraph lines. Coupling was either direct from line to machine or via perforated paper tape, speeds of 300 characters per minute were normal (2/6) (2/7).

It was only after the second World War with the advent of electronic computers, that higher speed printers became required. The earliest computers (1946) used punched cards or perforated tape for output. (2/8; 2/9; 2/10; 2/11; 2/12; 2/13). These cards or tapes were then fed to teleprinters which produced the final printed output. It is interesting to note that an early Russian Computer (1956) had a photographic output printer working at speeds up to 12,000 characters per minute (2/14).

The first high speed computer printers used the stock ticker principle of a rotating type wheel and a hammer. In order to print whole lines a number of type wheels were used one in each character position

Speeds of 150 lines per minute with 100 characters per line were obtained. In these printers the type wheel and paper were stationary at the time of impact of the hammer. The next advance was to strike "on the fly" a continuously rotating type wheel with a synchronized hammer. Speeds up to 1,000 lines per minute can be obtained with this mechanism. These mechanical printers and other non-mechanical printers of the 1960's are described more fully in section 3.2.

2.2 Context of Project

When this project was started in November 1963, the internal speed of electronic computers had far exceeded the speed of available output printers. Published data gave comparative figures of 90,000 characters per second for output to magnetic tape and 1,350 lines per minute for printed output. This latter figure gives a maximum of 3,600 characters per second (2/15). If a time factor of five to one is allowed for the magnetic tape output to be formatted the printing speed is still five times slower than the output speed of the computer. From this single comparison it must be realized that either the working of the computer must be slowed down during output or a large buffer store must be provided.

In a discussion on computer peripheral equipment in 1959, Royle(2/16) suggested that there were three a applications for a high speed printer. The first was to provide information to be used as input to further computers. The second was to perform short bursts of printing without holding up the computer. The third was to print large volumes of data. It is the second application which is of interest here and forms the basis of this project.

It was considered that a clear need existed for a computer output printer which could stop and start and print at a speed closer to that of the computer. This was thought to be of particular importance in the checking of programmes and for scientific computation. The printing, on a semi-continuous basis, of large amounts of data was not the main objective. This was thought to be better performed "off-line" from the computer via magnetic tape.

2.3 Overall History of Project

In the Autumn of 1963 it was decided to investigate the feasibility of constructing a high speed printer for use as a computer output device. It was specified that the printer should use un-treated paper, work at a speed of 5,000 lines per minute, either continuously or intermittantly with the output being immediately visible, a line at a time.

A literature survey was performed, in which existing printers were reviewed and possible printing methods examined, it was then decided to consider, in greater detail, a Xerographic type of printer. Such a printer would use a special cathode ray tube and suitable electronics to convert the computer output into lines of illuminated alpha-numeric characters. These characters would be projected onto a photosensitive surface thereby creating electrostatic images, which would be developed using dry ink particles. Finally the ink particles would be transferred to paper and fixed by heating.

It was known that suitable cathode ray tubes had been developed and it was decided that the starting point of this project would be the illuminated characters. A test rig was designed to investigate the exposure, development transfer and fixing stages. The final printer would employ a photosensitive drum, but the test rig was designed to use photosensitive plates which were readily available. This limited the operation of the test rig to single shot working. A negative photographic transparency was used as the source of illuminated characters. By the end of 1965 single sheets had been reproduced at speeds in excess of 5,000 lines per minute. Some tests had also been performed using half tone photographs. These were reproduced but at lower linear speeds.

At this stage it was clear that financial support from outside the University was required, to extend the work from single sheet to continuous operation. Support was not obtained and the Xerographic work was discontinued for reasons given in Section 6.

An alternative printing concept was then chosen for investigation. A focused laser beam would be scanned over the surface of a layer of powdered ink on paper. The beam would be suitably modulated to fuse the ink only where required. Such a printer offered the possibilities of producing alpha-numeric characters or half tone material. Simple tests were performed to estimate the laser power requirements. A literature survey revealed that of the existing lasers (1966) only the CO_2 laser, operating at 10.6µm wavelength, was capable of continuous working with power of the required order of magnitude.

A research programme was developed from mid 1966 onwards to investigate further some aspects of this printer. A CO_2 laser of 30 watts output power was constructed, based originally in its design on one made by the Services Electronics Research Laboratories at Baldock. It was subsequently redesigned to overcome certain difficulties encountered in the construction of the laser tube assembly and in the electrical system. The laser first operated early in 1967. Using Xerographic ink, some ink fusing tests were carried out with laser powers up to 10 watts. Microscopic examination of the fused ink particles was performed. The effects of paper texture, energy density and prior electrostatic charging were examined.

A theoretical study of the fusing mechanism was made. This was made more difficult by ignorance of the ink properties; the makers being unwilling to supply technical information.

Some of the other aspects of a laser printer, such as beam modulation and scanning, were considered but no practical work on these was performed.

3.0 Function and duty of Printers

In this section the general requirements of high speed printers are outlined and an ideal printer is specified against the background of existing printers.

3.1 Functional Requirements of Printers

The printers considered here are required to convert transient data into permanent visible images. The input is normally a series of coded electronic pulses representing characters and formatting instructions. The printer must produce characters and space them correctly. For "on-line" connection to a digital computer, the printer must be capable of intermittant operation for periods of random length and occurrence. When used "off-line" and fed by tape or cards the printer may be allowed to run semi-continuously.

3.2 Survey of Conventional Printers

This survey covers computer output printers which were described in published literature up to the end of 1970. Technical details of the newest printers are difficult to obtain for commercial reasons, hence the date of publication may be misleading. No attempt is made here to describe fully the mechanism of each printer. The disadvantages of each printer and the factors limiting its speed are outlined.

The printers are divided into those which employ mechanical means to produce the final printed characters and those which do not. Both "serial" and "parallel" mechanical printers are described. A serial printer uses one mechanism to produce characters in all positions. A parallel printer has a separate mechanism in each position along a line.

3.21 Mechanical Printers

All mechanical printers produce characters by the impact of a hard inked object upon paper. This object may be a complete character, as in a typewriter, or a series of styli selected to form a character.

The earliest high speed printer (1959) was of the parallel kind, using a rotating typewheel and a hammer in each position across the line. The type wheels were stationary at the moment of impact and typical maximum speeds were 150 lines per minute.(3/1). The speed was limited by the inertia of the typewheels.

A continuously rotating cylinder, with a set of characters in each position was used in the Shepard printer (1954) (3/2). The hammers were actuated to hit the paper against the wheel "on the fly". Speeds up to 1,300 lines per minute were achieved, but the printed lines tended to be wavey.

The Potter "flying typewriter" (1959) used a single horizontal typewheel rotating in front of the paper with a line of hammers behind. The paper had to form an arc, which limited the length of line. Speeds up to 600 lines per minute were claimed (3/1).

In the IBM 1403 (1962) chain printer, the typewheel was replaced by a continuously moving chain of characters. Speeds of 600 lines per minute with 132 characters per line were possible (3/3). The Potter chain printer, introduced in 1965 ran at the same speed but was mechanically simpler (3/4).

With both these printers the speed was reduced if a larger choice of characters was required. The factors limiting the speed were fully analysed by Greenblott (3/3). Basically a certain force is required to produce a clear image, if too much time is taken to apply this force blurring will occur. Small hammers produce insufficient force, large hammers have excessive inertia.

Two kinds of stylus printer are known to have been made. In the I.C.T. Samastronic (1959) solenoid operated cables actuated a line of styli, one in each character position, across the page width. As the paper moved, the styli vibrated across each character width. The information required to produce a particular character was stored on a disc. Speeds of 300 lines per minute were quoted (3/5).

The Creed mosaic printer (1958-1962) had a 5x5 matrix of hydraulically actuated styli which moved across the paper. In each character position the required styli were presented. The speed of this serial printer was said to be 100 characters per second. The 25 dot matrix produced inferior characters, and the hydraulic, electronic and mechanical complexities of this machine suggest problems of reliability (3/8) (3/7) (3/8).

3.22 Non-Mechanical Printers

Fig. 3.2.1 tabulates the features of the printers described within this section.

The first non-mechanical high speed printer for computers was used in a Russian computer (1952). This projected characters formed from a matrix of pin point lights onto normal photographic film. This was then developed and printed at normal speed. 200 characters per second could be printed (2/14).

Another early photographic printer (1959) used a set of opaque characters on a cylindrical concave surface which were illuminated as required by an unfocussed cathode ray tube. By means of an optical system including a square prism, to hold the image stationary, the illuminated characters were projected onto photo-sensitive material. No speed was quoted for this printer.(3/9).

A very simple printer (1963) used a cathode ray tube with fibre optic face and photosensitive paper with no intermediate optics. The image was fixed by subsequently passing the paper over a heated platen. Speeds of 6,000 characters per second were claimed (3/10).

All three of the systems mentioned so far had the disadvantage of using high cost photosensitive paper or film and of not giving visible access to each new line of output, because of the developing and fixing processes.

A more complicated printer which used a special cathode ray tube was first described by Oldin in 1957 (3/11) and again in 1961 (3/12). Lines of characters were produced by line scanning on the face of a thin window C.R.T. These characters had been copied electronically from single characters displayed on a Monoscope tube (3/13). "Electrofax" paper was exposed to the face of the C.R.T. This paper had an electro-photographic coating which was sensitized by electrostatic charging (3/14; 3/15; 3/16; 3/17; 3/18). After being charged and exposed the latent electrostatic image was developed using a mixture of thermo-plastic resin toner and iron filings. The toner particles which adhered to the paper were then fused by heat to form a permanent image. Speeds of 10,000 characters per second up to 150,000 characters per second were predicted (3/12).

Another printer which used Electrofax paper was the Stromberg Carlson S.C. 3070 (1963). The characters in this case were directly generated on the face of a "Charactron" Tube (3/19).

In this tube the electron gun generated an electron beam, focused it into the proper size, and directed it through the required hole in a matrix. A character shaped hole in the matrix formed the beam into the shape of the character. The shaped beam was then focused and positioned as required on the tube face. For printing purposes a rectangular fibre optic faced tube was used. The face was 220mm by 10mm allowing one line of characters to be displayed. Sixty characters were available with this printer, but Charactron tubes with 144 characters had been made.(3/20). The operating speed of this printer was given as 5,000 words per minute with 72 characters per line (or 120 characters per line if required). A whole line of 120 characters could be printed at a rate of 225 lines per minute. If fewer characters were required in a line the speed could go up to 500 lines per minute. The printer could be stopped and started for single lines of printing. The printed output could be viewed within 4 seconds of printing. The electrostatic image on the paper was developed by a rotating brush carrying particles of fusible toner.

An earlier printer (1958) made by the same Company (Stromberg Carlson) also used a Characton Tube but did not use Electrofax paper (3/21). In this machine Xerography was employed to produce the final print on untreated paper. The optical information from the Charactron tube was focused onto a selenium coated drum to form an electrostatic image, which was then cascaded with toner particles carried on glass beads.

The toner particles developed the latent electrostatic image. Paper was then brought into contact with the surface of the drum and the toner particles were transferred to it. The toner was fused to the paper to produce a permanent image. Speeds of 1,000,000 characters per minute were claimed for this printer. The commercial reasons for changing from Xerography to the use of Electrofax paper for the later printer are not known. The later printer was simpler but also slower because of the inferior sensitivity of Electrofax paper.

A British printer using Xerography was first reported in 1959 (3/22). This did not use a Charactron tube but a special C.R.T. in which characters were formed from a dot matrix (3/23). Printing speeds of 5,000 characters per second were claimed for this experimental printer. A life expection of 40,000 metres of paper for each drum was quoted.

The commercial form of this printer, the "Xeronic", was reported in 1964 (3/24). This had a page width of 290 mm. containing up to 128 characters from two small C.R.T.s each giving 64 characters. A speed of 2,800 lines per minute was quoted. Cascade development was used as in the early Stromberg Carlson printer (3/21). The Xeronic printer had additional facilities including a store of forms on microfilm onto which the data was to be printed. The machine was large and expensive and was designed for data processing requirements rather than for simple high speed computer output.

A different kind of Xerographic printer was reported in 1959 in which electrostatic information was produced on the drum directly (3/25). A cathode ray tube with conducting wires set in its face was in close proximity to the drum. The change in electrostatic charge on a wire, caused by the electron beam within the tube, produced a change in the charge pattern on the drum.

In 1960 another printer used a tube of the same kind to produce electrostatic images direct on coated paper (3/26) (3/27). 20,000 characters per second or 120,000 lines per minute were quoted for this printer. It was claimed that the coated paper cost only one tenth as much as photosensitive paper.

At the same time, another printer which also used coated paper for electrostatic imaging, produced the characters by means of a directly energized matrix of styli (3/28) (3/29), 1,000 volts was applied to the styli as required. The styli being held 10 µm from the paper to prevent wear. The paper was then pulled through an ink bath where toner particles adhered to the charged areas. Fixing was performed by passing the paper through a pair of heated rollers. This printer was rated at 3,000 words per minute. Speeds beyond 30,000 words per minute were expected with continuous line feed. Because of the nature of the development and fixing sections, the output was not immediately viewable. The neatest commercial version of this printer, the Gould 4800, was shown in the U.K. in 1970. This produced alpha-numerics or graphics, which could be viewed within one second, at 4800 lines per minute. Fluid development was used with no subsequent fixing.

In 1956 the first printer using electrosensitive paper was reported (3/30). This was a specialized device for recording weapon test results. There were only 4 character positions per line, but the speed was 150 lines per second. A 5x3 stylus matrix was used to form the characters. When current passed from a stylus through the paper, to a plate electrode behind it, a permanent mark was produced. No subsequent development or fixing was required.

A higher speed version of this kind of printer, rated at 180 lines per second with 12 characters per line, was working in 1957 (3/31). A commercial printer with 120 characters per line and a maximum speed of 31,250 lines per minute was available by the end of 1964 (3/32). This Radiation 690 printer claimed to be the fastest in the world. It was designed to operate off-line from the computer because of the difficulty of stopping and starting at this very high speed. The running cost of such a machine would be expected to be high because of the paper used; also the final contrast would be poor.

Magnetic printers have been reported in the U.S.A. in 1957(3/33) and in Japan in 1962 (3/34). These machines used coated paper on which magnetic images were produced by a row of electromagnets. Development was by finely divided magnetic ink powder with a thermoplastic base. Fixing was performed by fusing the ink to the paper. The characters produced were not of the highest quality; the limitation of resolution being the size of the magnetic pole pieces.

In 1967, a magnetic printer producing 500 characters per second with superior resolution was demonstrated (3/35). Electromagnetic styli, spaced at 6 per mm., produced a magnetic pattern on a rotating drum which was then developed with finely divided ink. The ink particles were pressed onto the surface of the paper and fixed by heating. Speeds of 60,000 characters per second were predicted.

Some experimental electrochemical printers are thought to have been made. It seems doubtful whether very high speeds can be obtained in this way because of the chemical reaction times involved and the very high current densities required (3/36).

3.3 Ideal Specification for Computer Printer

The ideal computer printer would:-

1. Produce a permanent record of the output data unaffected by normal temperatures and humidities and reasonably resistant to defacement by abrasion.
2. Normally use standard typeface but should not be limited to a single font.
3. Have a printing speed compatible with the computer output capability.
4. Print on-line to the computer; not off-line via paper or magnetic tape.
5. Make each line visible directly after printing.
6. Stop and start for single lines at random moments in time.
7. Be capable of spacing horizontally and vertically using non-character signals from the computer.
8. Be quiet and safe in operation.
9. Use inexpensive untreated paper in an easily handled form.
10. Be cheap to run.
11. Be reliable, rugged and foolproof

4.0 Identification of Research Programme

The literature survey had shown clearly that mechanical printers could not be considered for operation at speeds above 1,500 lines per minute. In the field of non-mechanical printers, the areas which appeared to be most worth considering were electrophotographic and magnetic. Consideration was given to the construction of a magnetic printer; this was not pursued because it was considered that magnetic elements could not be made small enough to give satisfactory resolution.

The specific electrophotographic process finally chosen is most commonly known as Xerography. In this the electronic information is displayed optically and projected onto a photoconducting surface. The image is developed with dry ink powder which is transferred to paper and fixed. The system has the advantages of using untreated paper and giving output of high contrast.

The features of the printer requiring investigation were the development and fusing at high speed. The published literature at this date (late 1963) contained few technical details.

The conversion of electronic information to optical characters was considered to be outside the scope of this work. Reference is made in Section 5.13 to existing methods.

In order to investigate the development process an electrostatic image had to be produced. It was decided to construct a test bed on which all processes could be tried.

A target speed of 5,000 lines per minute was decided upon. The aim of the research programme was to demonstrate the feasibility of all the sections of a Xerographic printer at the target speed. It was also required to determine the theoretical upper speed limit of each of the sections.

5.0 Xerographic Work

5.1 Introduction

In this section Xerography is explained, the proposed printer is specified and the research areas identified.

5.11 Xerography

The late C. F. Carlson used the name Xerography to describe the technique of electro-photographic "dry-writing" which he invented and patented from 1939 onwards (5/1) (5/2). These and subsequent patents are listed by Newman (5/3). Carlson's early work is described by Dinsdale (5/4). The progress in the field is listed up to 1958 by Dessauer (5/5) and up to the beginning of 1963 by Claus(5/6).

Fig. 5.1.1. shows diagramatically the basic stages of Xerography. A selenium coated aluminium plate is used. It is passed, in darkness, under a fine wire having a potential of 5 - 10 kV relative to the plate (1). This creats by corona discharge a surface charge of a few hundred volts (2). The plate is then exposed to a pattern of light (the letter'E'in the diagram). This causes a selective loss of charge on the surface; the dark area remaining charged, the illuminated area losing its charge (3). The electrostatic image so formed is developed using a finely powdered dry ink.(4). Transfer to paper is achieved by placing paper on the inked surface and subjecting it to a negative corona discharge (5). This image is finally fixed, when the paper has been removed from the plate (6), by radiant heating which fuses the ink particles to the paper surface (7).

After transfer the plate may be cleaned, to remove any stray ink, and then re-used. For most applications a drum is used instead of a plate. The various stages are arranged at fixed locations round the drum which is rotated.

5.12 Specification of Proposed Printer

The proposed printer would be similar to the early Stromberg Carlson printer described in Section 3.22 (p.13), Fig. 5.1.2 shows the components of the machine. Like the Stromberg Carlson printer it would use a Xerographic drum and a special C.R.T.; development, however, would not be by the cascade method, but by means of a powder cloud or "aerosol". The fixing of the final image would be performed at high speed, a line at a time rather than by simple slow radiant or conductive heating. The paper movement would be dis-continuous to allow for the printing after random time intervals. The output would thus be visible a line at a time. The design speed would be 5,000 lines per minute; slower than the 7,000 lines per minute quoted for the S.C. printer, but four times faster than a mechanical printer.

5.13 Selection of Items for Research

The printer described in outline in Section 5.12 involves a number of processes:

1. Charging the photosensitive surface (the drum).

2. Producing illuminated characters to which the plate is then exposed.

3. Developing the electrostatic image by powdered ink.

4. Transfering the ink to paper.

5. Fusing the ink.

6. Cleaning the drum.

7. Moving the paper as required.

We now consider the seperate processes against the background of the information available at the end of 1963.

1. Although Xerographic copying machines were available at this time, and some work had been published on the nature of electrostatic images; there was no clear guidance available relating to charging. It was, therefore, necessary to adopt an empirical approach. This is described in Section 5.22.

2. Many systems are available for the generation of alpha-numeric characters on normal C.R.T.s (5/7) (5/8) (5/9) (5/10) (5/11). Boyd (5/12) gives a survey of character generators. Spirer and Murray (5/13) also list special C.R.T.s; two of which have already been described in Section 3.2; the Charactron tube (3/20) and the dot matrix tube (3/23). Although not all these systems had been described by 1963, it was known that the problems had been overcome, and that research in this area was not required.

3. Aerosol development was chosen in the hope that it would be superior to the cascade method when considering drum wear, resolution and dark area development. Bickmore had described low speed aerosol development in 1960 (5/14). but no reference had been made to high speed aerosol developemtn up to 1963 and this therefore represented the main area for research.

4. The transfer of ink from the drum to paper was known to have been performed at high speeds (3/21). The approach had however to be expirical as in (1) above, since no details were available.

5. It was intended to study various high speed fusing methods including R. F. heating and the use of lasers.

6. Various drum cleaning methods were to be considered.

7. Paper trsnsport systems were to be studied at a later stage.

5.2 Design and Construction of Test Rig.

In Section 5.13 the aerosol development of electrostatic images at high speeds was identified as the main research objective. A test rig was designed to produce these images and to present them for development at the design speed of 5,000 lines per minute. Fig. 5.2.1 is a diagram of the test rig, a photograph of which, in its completed form, is Fig. 5.2.2. For the electrophotographic medium, use was made of Xerographic plates which were available in a used condition. These were carried by parallel belts over the charging, exposure and development areas. Illuminated characters were projected onto the plate from a photographic negative on a cylinder. The main frame and drive system were made first followed by the charging and exposure sections. Plates were developed first by hand to establish the existance of electrostatic images. The aerosol development section was constructed later, together with the transfer section.

5.21 Mainframe

The main frame of the rig was designed to be of sufficient length to accomodate the experimental sections and to ensure that the plate would travel smoothly. A belt speed of ½m/s was taken as normal to give 100 lines per second with a typical spacing of 5 lines to the inch. This speed allowed a margin of 20% over the printer speed of 5000 lines per minute. A variable speed motor drive was used with a speed capability in excess of five times design speed.

Continuously woven flat cotton belts were used, running along metal plates with inset ball bearings at intervals of one quarter plate length. Crowned pulleys were used on adjustable shafts, one at each end of the frame. The parallelism of these shafts was found to be very critical to the true running of the belts.

5.22 Electrostatic Charging System.

The available literature suggested that a D. C. potential of 5 to 10 kV and a current capacity of 50 to 100μA would be suitable for plate charging. An E.H.T. supply was built to run from mains voltage. For safety reasons an R. F. oscillator circuit was employed with high output impedance and very little smoothing capacity. A potentiometer in the grid circuit allowed the output to be varied. Additional safety features included a spring loaded on/off switch.

The plate charging unit was developed over a period of several months. The variables involved were wire material, surface finish and diameter and the spacing between wire and plate. To produce an even corona discharge without sparking was found to be possible but only after tests had been made with several different kinds of wire. Eventually tungsten wire was chosen because of its strength and stability and 100 µm was found to be the optimum diameter. Various support frames were tried, the final one, which eliminated sparking, was machined from solid perspex. Up to three parallel wires were tried but finally a single wire 10 mm from the plate was found to be best.

The wire potential was measured by an electrostatic voltmeter. The charging current was measured initially with a milliameter. This was found to be erratic and a U. V. recorder was used for all later current measurements.

5.23 Optical System

A photographic negative of lines of random numbers was used in place of a C.R.T. display. This negative was wrapped round a pyrex cylinder with an internal lamp and reflector. The lamphouse was stationary while the cylinder was rotated by the cotton belts. The peripheral speed was thus always the same as the plate speed. A "one to one " projection system, consisting of two front-silvered mirrors and a lens, focussed the illuminated portion of the cylinder onto the plate. In this way the characters did not move relative to the plate. The exposure time could be varied by means of an adjustable slot at the exposure station.

The level of illumination could be adjusted by stopping down the lens (f/2.9 to f/8) or by changing the lamp voltage.

Poor initial design of the lamphouse resulted in rubbing between it and the cylinder with consequent variation of speed. This problem was overcome in the final lamphouse.

5.24 Inking System

For aerosol development a steady and even flow of air-borne ink particles was required at the plate surface. These particles had to be electrostatically charged; positively for black on white, "positive" printing or negatively for white on black, "negative" printing. Fig. 5.2.5 is a diagram of the inking system. Compressed air was blown through a vibrated ink pot causing ink to move up through a tube and perforated manifold. The ink stream was diluted by re-circulated air from a motor driven centrifugal fan. The ink cloud passed through a charging grid, supplied with up to 10kV, before impinging on the plate. A vacuum hood was provided to remove surplus ink when a plate was absent because of the single shot operation of the rig. Various methods were tried for fluidizing the ink in the pot; including a 50Hz vibrator as shown in the diagram. In another method the base of the ink pot was formed by an earphone diaphragm energized by a variable frequency oscillator. The frequency was adjusted to achieve optimum fluidization.

5.25 Transfer Section

The transfer unit was mounted above the belts and could be supplied with 10kV of either polarity. Its design incorporated the proven features of the charging unit.

5.3 Experimental Xerography

In this section the experimental printing performed on the test rig is described together with some preliminary work on corona discharge. Calibration tests, with their results, are described in Appendix Section 10.2.

5.31 Corona discharge tests

In order to relate print quality to plate charging current, the latter had to be determined. A U.V. recorder was employed because of the transient nature of the tests, but it was not convenient to use it for every printing run. Experiments were therefore performed to determine the relationship between charging current and the open circuit voltage on the wire. In some tests the transient voltage was also recorded to determine the impedance of the circuit. Plates were normally run at the design speed. Tests at other speeds did not reveal any measurable change in the relationship between current and voltage. The results are shown for positive and negative wire potentials by Fig. D and Fig. E.

5.32 Printing Runs

The highly sophisticated instruments required for the direct measurement of electrostatic images were not available. These images were thus only detectable by development with fine powder. Commercially available Xerographic toner (ink) was used for the experimental work. Prior to constructing the aerosol inking section, manual cascade development was employed to study the image producing processes.

5.321 Manual Development

A developing tray, 20 mm deep and the same size as a Xerographic plate, was used. The plate fitted against a seal in the top rim. The developing medium consisted of a mixture of Xerographic toner and Xerographic developer (small vitreous spheres).

A typical printing run was conducted as follows:- The belt speed, illumination level and charging voltage were set to their required values and all lights except that within the cylinder were put out. A freshly cleaned plate was placed, face downwards, on the belts at the L. H. end of the rig whilst the E.H.T. supply was switched on. Having passed over the charging and exposure sections the plate was removed from the R. H. end and placed, still face downwards, in the developing tray. With the plate held against the seal, the tray was inverted and the contents cascaded over the plate surface by tilting the tray. The tray having been re-inverted the plate was removed and examined in the light.

It was soon discovered that, with sufficient toner, the duration of the development process was not critical. In order to display the developed images, some was transferred to paper as described in Section 5.3.3.

Tests were performed over a wide range of speeds, charging currents and illumination levels. The results of these tests are illustrated by Figs. 5.3.1-3. It should be noted that subsequent reproduction has reduced the clarity of these prints and that the originals were obtained using worn and scratched plates.

Fig. 5.3.1 shows a typical section of a page produced at the test speed of 100 lines per second. At higher speeds, fainter images were produced; the upper limit being at about 400 l.p.s. with the illumination level available. Images produced at high speeds tended to be too faint to transfer well and could not be reproduced. The charging current had to be optimized for each speed to produce the best image contrast.

Fig. 5.3.2 shows the effect of charging current value upon print quality at the rated speed. High currents produced dark characters but also exagerated the background scratches and other plate imperfections. Low currents produced weak characters. The optimum charging current at this speed was about 30µA. The use of positive and negative transfer potentials is considered in Section 5.3.3.

Fig. 5.3.3. shows the effect of illumination upon print quality with a charging current of 30µA at the rated speed on 100 lines per second. The effect is the obvious one of increasing density with increasing intensity of illumination. Some characters were legible at illuminations as low as 15 lux, i.e. one quarter of the maximum. This is consistant, from reciprocity considerations, with results mentioned above, of characters being reproduced at four times normal speed with maximum illumination. 30 - 40 lux was found to be adequate for good printing.

5.322 High Speed Aerosol Development

The development section used for high speed inking has been described in section 5.24. The procedure employed in the printing runs was essentially the same as that described in Section 5.321. In addition, the ink circulating blower, compressed air and vacuum cleaner were switched on as the plate was carried along the belts. Thus the plate was developed by the time it reached the right hand end of the test bed. Examples of printing produced are shown in Fig.5.34. Precise control of the ink quantity on these single shot printing runs was impossible. They did however clearly demonstrate that aerosol development could be used at speeds above 100 lines per second. The dark areas on the prints are due to inhomogeneities in the aerosol,both spatial and electrostatic. Various charging grids within the inking system were tried and potentials up to 10 kV were used. In some cases this gave rise to sparking onto the surface of the plate with resultant damage. Many of the difficulties experienced resulted from the single shot operation.

5.33 Image Transfer to Paper

The procedure for transferring the ink from the plate was as follows:- having developed the plate by hand or at high speed, the plate was placed face upwards on the belts again at the left hand end of the test bed; A sheet of paper was placed on the plate which was then carried by the belts under the transfer unit, which was supplied from the E.H.T. unit. Fig. 5.3.2. shows the effect of positive and negative potentials on the wire. With positive polarity white figures were produced on a black background; with negative polarity, the required black figures were produced on a white background, (this was for the original charging potential being positive).

The potential required for transfer did not appear to be critical. Normally the maximum was used which did not result in sparking from the wire to plate. It was found possible to transfer the ink from the plate to the paper at speeds of at least 100 lines per second.

Different kinds of paper were tried and transfer occurred to all but the very thickest. Ordinary thin typing paper was found to be entirely satisfactory. Subsequent to the transfer operation, the ink was fused by exposure to radiant heat.

5.34 Half Tone Working

Some experiments were performed using a pictorial photographic negative instead of the negative of random numbers. A number of poor quality prints were obtained using high speed inking. The dark areas were continuous and did not suffer from "dark edge" effects of the kind typically found with cascade development. Equivalent speeds of up to 25 lines per second were used. An example is shown in Fig. 5.3.6.

5.35 Summary of Experimental Findings

For plate charging a single tungsten wire 100 µm diameter spaced 10 mm from the plate was found to be suitable. The corona potential threshold was about 5 kV and at 7.5 kV the current for the 280 mm length was 100 µA (i.e. 360 µA/m).

The charge per unit area required for the production of satisfactory images was between 120 and 280 $\mu C/m^2$.

Satisfactory images were produced with exposures of 10 ms with illumination levels from 25 to 65 lux. (hence 0.25 to 0.65 lumen.s/m^2).

Aerosol development was shown to be feasible at speeds in excess of 100 l.p.s. (0.5 m/s)

5.4 Comparison of Experimental Results with Theory

Since the object of this work was to determine the feasibility of certain ideas, the approach was essentially qualitative. The measurements taken were for considerations of reproducibility rather than absolute accuracy. The inner workings of the Xerographic process in terms of potential gradients in the selenium were not studied. The most comprehensive literature on the overall subject was not published until the experimental work described here was in its final stages in 1965 (5/15) (5/16). There are however certain areas in which the experimental findings may be compared, if not with theory then with other published results. These areas which are discussed below are; corona discharge and plate charging, the photosensivity of selenium, and the aerosol development of electrophotographic images.

5.41 Plate Charging

The current passing from a fine wire to a plate parallel to it is dependent upon the potential difference. A threshold voltage must be exceeded before a corona developes allowing current to pass. For the wire diameter and spacing used here the threshold potential was found to b be 5 kV (Fig. D). This compares favourably with the figure of 4.3 kV quoted by Schaffert on page 183 (5/16). With increase in voltage, there is an increase in current (though precise relationship is masked by the characteristics of the E. H. T. Supply, Fig. D is plotted on the basis of no load voltage, chosen for consistency of setting from one test to another).

Taking a spot check at a high current rating of 100 μA, experimentally the applied voltage was 7.5kV (the open circuit voltage 8.5kV minus the voltage drop in the circuit 1kV). From Shaffert the voltage was 7kV for the same current per unit length. Considering the variations which can be expected from the effects of humidity and wire and plate surface condition these figures are in fair agreement.

The current required to charge the plate at a particular speed in order to produce a suitable sensitivity was measured and noted in Section 5.35 (120 and 280 $\mu C/m^2$). The capacity of the selenium layer is about 1 $\mu F/m^2$ according to Dessauer p.201 (5/16). Thus the potential produced was some 100 to 300 volts. This agrees with the value of voltage expected; the maximum plate potential quoted in the general literature being 600v. This should not be considered to be more than a check on the order of magnitude since edge effects were ignored and the selenium thickness was not known.

5.42 Photosensitivity of Selenium

Satisfactory images were reproduced with exposures from 0.25 to 0.65 lumen.s/m^2. Starr (5/17) relates plate potential to exposure for amorphous selenium. Since vitreous selenium was used here, a factor of ten must be applied to the sensitivity (5/5). Hence a reduction of plate potential from 100% to 75% (for 25 lux) or 50% (for 65 lux) is predicted. This reduction in plate potential in the illuminated areas is sufficient to give a reasonable developed image.

From Fig. 5.33 it can be seen that the limit of illumination was in the region of 15 lux with a resulting potential change from 100% to 80%. For cascade development, a print density of unity can be obtained with an electrostatic contrast of 100 volts, according to Dessauer p.294 (5/15). This is consistent with the 25%-50% reduction from 300 V calculated in Section 5.41.

5.43 Development and Transfer

It can be readily seen from Fig. 5.3. 2 that the processes of development and transfer must be considered together. When the ink particles come in contact with the plate they adhere according to their charge. These charges are not fully neutralized as can be seen from the difference between the positive and negative transfer images. The cascade developed images when transferred with negative potential behave as one would expect.
Low charging currents and hence low initial plate potentials gave poor images. Excessive currents accentuated the plate imperfections (scratches and worn areas) without enhancing the image contrast.

High speed aerosol development yielded better images than might have been expected. The published work (5/14) (5/18) (5/19) (5/20) deals only with low speed development (up to 0.01m/s.) There appears to be no indication that speeds of 0.5 m/s., which were achieved here, were even contemplated.

Nevertheless there would appear to be no fundamental reason why this speed should not be exceeded. So long as sufficient charged ink particles can be brought near to the moving drum or plates, development should take place.

5.5 Programme of Future Research at time of Project Re-appraisal

Having established the feasibility of printing single sheets at design speed it was intended to progress to continuous operation. A second test rig was designed, based on the proposed printer, using a photoconducting drum. With this it was proposed to improve the development section in particular. The cleaning of the drum could also be performed. Initially continuous paper feed was to have been employed but intermittent feeds were to be investigated. A theoretical study of the limitations of the aerosol development process was to be made. The rapid fusing of single lines was also to be studied. An initial literature survey suggested the following possible methods:-
lasers, microwaves and R. F. induction heating.

5.6 Conclusions

The aim of the Xerographic work had been to establish the feasibility of certain parts of a high speed printer. Working on a single sheet basis, optically generated characters were converted to a permanent visible form at the design speed of 100 lines per second. The novelty of the work lay in the use of aerosol development at high speeds. Other components of the test rig could have been made to work more quickly if some of the work relating to current commercial machines had been published at the time rather than later. Comprehensive literature was available in 1965, by which time this work had been completed.

The quality of the printing was not first class primarily because of the worn state of the selenium coated plates employed. The variation of ink density was due to the intermittent nature of the printing process. Much of this would have been eliminated in a printer using a drum instead of plates.

No attempt was made to assess the quality of the electrostatic images because of the complexity of the instrumentation required.

In those areas where the experimental findings could be compared with the published findings of others, there was general agreement. In the main area under investigation, high speed aerosol development, no published results were discovered.

The limitations in speed of printing which were encountered were due to lack of illumination of the optical characters. For continuous printers other limitations might be imposed by the requirements for drum cleaning between transfer and recharging. No experimental work was possible in this field. In the aerosol development process there must be some upper speed limit in terms of ink particle velocity.

The possibility of printing half tone material in addition to alpha-numeric characters has been mentioned. The experimental results obtained were of poor quality and much further work would be required before a realistic assessment could be made of this method as the basis for a multipurpose high speed printer.

6.0 Project Re-appraisal

By the end of 1965, the experimental work using flat Xerographic plates had been completed. It was considered that financial and practical assistance would be required for the work to be continued satisfactorily.

The National Research and Development Corporation when approached, showed interest in the project but were unable to provide assistance. An application was made to The Science Research Council for a grant and at the same time Rank Xerox were asked if they would be prepared to supply a selenium coated drum. In reply Rank Xerox said that they were unable to supply a drum for commercial reasons; in addition they were at pains to point out the considerable difficulties involved in the project and the effort already expended by their American associates the Xerox Corporation.

The S. R. C. in rejecting the application for a grant made some important comments. The first was that the advent of time sharing computers and improved buffering facilities had reduced the need for high speed on-line printers. Secondly the demand for on-line printers was being reduced by the increasing emphasis on direct access by remote terminals. Thirdly there seemed to be a feeling that the majority of computer users were satisfied with 600 lines/ minute printers. Fourthly they pointed out the disadvantages of the Xerographic system in terms of the need for frequent replacement of selenium coated drums because of wear. The final and most important comment was that: " there may well be a need, in about five years, for computer output devices which can produce alpha-numeric anotated line and possibly half tone images, the best solution to this problem is not, however, at all obvious at the present time".

In view of these comments and the lack of material support from Rank Xerox, it was reluctantly decided to discontinue work on the Xerographic Printer.

It was still felt however, that a need existed for a new form of high speed printer capable of alpha-numeric and half tone output.

In connection with the fusing section of the Xerographic printer, a preliminary study of lasers had been made. One idea which was put forward was to print by burning holes in paper using a focussed laser beam. It was realized that laser power of tens of watts would be required. In 1965 lasers with high continuous power outputs were first reported. Simple experiments were performed to determine the energy density required for scorching paper. In the course of these tests, it was discovered that there was a better method than scorching; the fusing of small areas of Xerographic ink. The energy density required was about five times less than that required for scorching, and the contrast produced was superior.

It was decided to pursue this investigation further with a view to constructing a direct fusing laser printer as described in Section 7.

7.0 Direct Fusing Laser Printer

7.1 Introduction

In the following sections a proposed laser printer is described together with the experimental and theoretical work which was carried out to determine the feasibility of the principle process involved: fusing by laser energy of powdered ink on paper.

7.11 Description of Proposed Printer

The basic concept of this printer would be to produce images by fusing discrete areas of powdered ink onto the surface of untreated paper. Initially the paper would be covered with a thin continuous layer of dry powdered ink particles, these particles would adhere to the surface because of electrostatic forces induced by a corona discharge. The ink layer would then be scanned in lines across the paper by a focussed laser beam. The beam power would be modulated so that some areas would receive more energy than others. The beam control would increase the power where a dark area was required causing the ink to fuse to the paper. By scanning over an area a complete image would be produced by the fused spots.

In another form of the printer, the scanning speed would be variable but the beam power would be constant. The beam would move slowly over areas to be fused, and fast over areas required to remain white.

After the scanning process, the surplus unfused ink would be removed by a vacuum system. The power modulation, or speed variation, would be controlled either electronically from a buffer store of the computer, or by the electro-optic scanning of characters displayed on a C. R. T.

This printer would not be limited to the production of characters but could also be used for half tone work.

It would satisfy nearly all the requirements set down in Section 3.3. for an ideal computer printer. The accessibility might be limited to the line before last but manual forwarding could be arranged for one line without destroying the layout of the final print out.

7.12 Programme of Research

The printer described in Section 7.11 had five major sections: an electronic control for the modulation and scanning, a paper transport system, an ink spreading and charging system, a laser scanning and power modulation system and a surplus ink removal section.

It was considered that the feasibility of the whole printer depended principally upon the feasibility of the laser system for fusing the ink onto the paper. It was therefore decided to examine the ink fusing mechanism from an experimental and theoretical point of view. The aim was to determine the effects of energy density, scanning rate, paper texture and prior electrostatic charge upon the quality of the fused image.

For the experimental work, a high power laser was required, and a literature survey was to be initiated to determine the most appropriate type of laser.

A theoretical study of the fusing process from the point of view of heat transfer was also to be undertaken.

If the results of the fusing work were satisfactory, the other sections of the printer were to have been examined in detail, if time allowed.

7.13 Choice of Laser.

Preliminary experiments (mentioned in Section 6.0 p.43) suggested an energy density requirement in the order of .03 Joules / mm^2. For the printing of alpha-numeric material in lines 5 mm wide and 200 mm long at 5,000 lines per minute, a mean power of 250 watts would be required. (This assumes 10% of total area is black). At the time when these sums were done (March 1966) some lasers of this power had been reported. These were gas lasers using a mixture of carbon dioxide, nitrogen and helium and producing radiation of 10.6 μm wavelength (7/1) (7/2) (7/3) (7/4). No other laser, solid, liquid or gaseous had been reported with a continuous output of this order of magnitude. The fact that many kilowatts could be produced in small bursts by several other kinds of laser was not relevant, since their mean power was only in the order of milliwatts.

The operation of the CO_2 laser at 10.6 µm wavelength has disadvantages. Glass optical components cannot be used above 3 µm, therefore sodium chloride, potassium bromide or sintered zinc sulphide have to be used. The first two materials have good optical properties, and are cheap but are adversely affected by moisture. Sintered zinc sulphide (Irtran 2) is expensive and has lower transmission but is more durable.

The H. F. modulation of the laser beam at 10.6 µm had not been achieved. Modulation by means of altering the electrical supply to the tube was only effective up to 1 kHz. Other external methods of modulation were being tested in 1966 and are referred to in Section 7.7.

7.2 Design and Construction of Laser

The basic design of the CO_2 laser, used for this work, was obtained from the Services Electronics Research Laboratory Baldock. After consultation with the experts from S.E.R.L. it was decided that a laser of 30 watts nominal output would be suitable for the work and could be constructed at reasonable expense.

The laser consisted of a water jacketed pyrex tube, 30mm bore and 2m long with a mirror and an electrode at each end. By supplying about 10 kV across the electrodes, a current of 50-100 mA passed through a mixture of gasses (1 part CO_2, 2 parts N_2, 10 parts He) in the tube at a pressure of 10 torr. The mirrors were stainless steel coated with gold; one concave and the other plane with a central hole, covered by a window; through which the beam emerged.

7.21 Overall Design

A self contained laser unit was required which needed only to be plugged into a 13A single phase 240V socket, and supplied with mains cooling water. A design was arrived at in which the main cabinet containing the electrical power supply, together with the controls and instrumentation, was used to support the detachable horizontal laser tube. The vacuum pump and gas cylinder were mounted on a small trolley. The height of the horizontal output beam was kept well below eye level.

The main cabinet was of rigid construction to reduce vibration and to be strong enough to support the D.C. power supply which weighed about 50 kg. The cabinet was totally enclosed for electrical safety. The instruments and controls were mounted on a sloping panel at the top for ease of operation.

The pyrex laser tube was supported in rubber mountings to reduce tube vibration. The tube with its mirrors and electrodes was enclosed by a perspex cover for electrical safety. Holes were provided in the ends for the output beam and to allow for the adjustment of the mirrors.

Fig. 7.2.1 is a photograph of the laser tube and control panel.

7.22 Optical System

Two mirrors $1\frac{1}{2}$m apart were used; the one at the R.H. end being concave with a focal length of 10m, the other being plane with a central 5mm diameter hole. Both were made from gold coated stainless steel 30mm diameter and $12\frac{1}{2}$mm thick. Stainless steel was used in preference to glass because of its thermal stability. Gold was used because of its high reflectivity at 10.6μm wavelength, although it was found to be very susceptible to damage from mishandling. Fortunately departmental vacuum coating facilities were available for re-coating the mirrors, once the damaged gold had been removed.

Two materials were used for the window which fitted into the plane mirror, Potassium Bromide and Irtran 2. Most of the experimental work was performed using an Irtran 2 window because the other windows clouded over rapidly from exposure to moisture making initial visual alignment impossible.

7.23 Mirror Mounts

The mirrors had to be mounted in such a way that an air tight seal was maintained while allowing for angular adjustment. Initially the S.E.R.L. design of mirror mount was employed. An aluminimum flange was cemented onto the tube end with epoxy resin (Araldite). A second flange, into which was cemented the mirror, was supported from the first by stainless steel bellows. The flanges were kept apart by a tie bar and two adjusting screws. (Fig. 7.2.2.a) Difficulty was experienced with the sealing of this type of mirror mount.

A new type of mount was designed and tested. Rubber 'O' rings were used to seal the mount to the tube and to give the required flexibility for mirror adjustment. Fig. 7.2.2b shows a section through the mirror mount. Fig. 7.2.3. and Fig. 7.2.4. show the mount in position and the components respectively. The mounts were found to be satisfactory in operation from the points of view of sealing and positional stability. Fine adjustment was found to be rather difficult and finer screw threads could have been employed to advantage.

A later modification was to incorporate water cooling tubes on the mirror retaining plates.

7.24 Vacuum System

The working pressure of the laser was 10 torr and small quantities of air in the gas mixture were known not to be detrimental. A single stage rotary vacuum pump was therefore sufficient, giving a maximum rated vacuum of $\frac{1}{4}$ torr. Fig. 7.2.5 shows a diagram of the system.

The vacuum pump was connected to the tube through a diaphragm valve via one of the electrodes. The other electrode gas connection was through a needle valve to a cylinder of mixed gas. The electrodes were sealed to the tube with epoxy resin. The mirror mounts used 'O' ring seals.

The laser was operated with a positive gas flow from the cylinder to the vacuum pump. Complete vacuum tightness of a high order was therefore not required. The static leak rate was tested from time to time and was found to be of the order of 5 lusec. For normal laser operation, the needle valve opening of 10 divisions gave a gas bleed rate of 100 lusec. This was equivalent to 1 complete gas change every $1\frac{1}{2}$ minutes.

The gas mixture was made in the laboratory in a gas cylinder to a pressure of 120 kN/m^2 from bottled helium and carbon dioxide and atmospheric air. Nitrogen was not used since no conclusive evidence had been published to show that it was superior to air.

7. 25 Electrical Supply

Two alternative electrical power supply systems were used to drive the laser. For A. C. operation a neon sign transformer was employed. The primary of this was connected to the 250 volts mains supply. The output was connected directly to the laser electrodes. Because the transformer was designed with its secondary winding centre tapped to earth, neither of the laser electrodes could be earthed. The tube voltage was measured with an electrostatic voltmeter. The tube current was measured by inserting an ammeter between the two halves of the secondary winding of the transformer. In this way the ammeter was at earth potential. Typical output current and power characteristics for this transformer are given in Fig. G.

No trouble was experienced with starting using A.C. The combination of the characteristic high no-load and the peak voltage for each cycle, enabled conduction to take place within the tube at pressures up to 16 torr.

For D. C. operation of the laser a variable output power supply was constructed. Initially it was thought that a supply of 5 kV and 250 mA was required. A system was constructed, using thermionic valve rectification, to meet this specification. It was found that a higher voltage and a lower current were in fact required.

A second system was constructed. In this case a number of silicon diodes were used in a voltage doubling circuit to obtain a no load voltage of 10 kV. Trouble was experienced with this circuit because of diode failures.

The individual diodes tended to fail when subjected to the maximum inverse voltage. In each diode chain, the failure of one diode increased the voltage on the remainder, leading to a chain reaction in which all failed.

In the final power supply, shown diagrammetically in Fig. 7.2.6, Silicon Diodes were again used. Protection was provided against current surges by introducing a series resistance (125Ω); a fuse (500 mA) was also provided to protect against persistant overloads. It had been discovered that the fuse provided no protection against short current overloads since in this case the diodes failed first.

To protect against inverse voltage overloading two precautions were taken. A larger number of diodes was used, 13 on each side each rated at 1000V instead of the original 10. Each diode was shunted by a resistor (2.5 MΩ) to equalize the voltage drops along the train.

Variation of output voltage was obtained by means of a "Variac" variable ratio transformer through which the main H. T. transformer was supplied.

Protective circuits were provided. In order to eliminate the possibility to accidental switching on of the supply a main trip circuit was included. No power could be supplied to the H. T. transformer while this circuit was broken. Included in this circuit were a key switch to prevent unauthorized use of the system and an emergency stop button. Any number of other switches could be added to the circuit to prevent operation whilst the apparatus was uncovered, e.g. due to the removal of the laser tube cover.

Having been tripped out a trip reset button had to be depressed to reactivate the main supply.

An overload current cutout was also provided to limit the current drawn from the system. Again manual resetting was required after tripping out had occurred.

A wire wound 15 K Ω resistor was included in the line from the power supply to the live electrode. This limited the surge current when switching on the laser. Water cooled aluminimum electrodes were used for both A.C. and D. C. operation. The mains water was found to be of high resistivity and only small leakage currents were measured (5 mA). At inlet and outlet of the cooling water, 2m length of small bore tube were left and the extreme ends were earthed.

7.26 Output Power Measuring Devices

It was required to determine the power output of the laser in order to relate it to the printing performance. Absolute precision was not required but consistant and repeatable measurements were needed. It was decided to employ the simplest possible means. This involved measuring the rate of temperature rise of a mass of metal when heated by the laser beam.

The beam diameter was about 5 mm. The mass to be heated was a short length of 6 mm bore copper tubing. One end was left open for the beam to enter, the other was flattened onto a copper/constantan thermocouple junction.

The cold junction was held in melting ice. The e.m.f. produced was recorded against time on an X - Y plotter. With maximum gain, the Y scale was about 0.45K per mm. The X scale of time was variable.

It had been intended to compare the output measured in this way with results from other methods. A flowing water calorimeter was considered. Lack of time prevented the construction of other measuring devices.

7.3 Description of Experimental Work

This section describes experimental work performed to assess the feasibility of the direct fusing printer using a low power laser. The energy density required to produce satisfactory printing was determined at different speeds. The effect of paper texture and electrostatic charging of the ink were examined. Printing tests were performed with the laser operating on A. C. and D. C. Microscopic examination was made of the fused ink.

The laser output power measurements are described in Appendix Section 10.24.

7.31 Application of Laser to Ink Fusing

The turntable apparatus shown in Fig. 7.3.1 was used in tests designed to evaluate the effects of speed, power and paper texture upon ink fusing. The horizontal laser beam was deflected vertically downwards by a mirror which could be moved along the beam. The beam was thus made to impinge at any given radius on a horizontal turntable. The beam was brought to a focus on the turntable surface by a sodium chloride lens of 100 mm focal length. The effective beam diameter on the turntable surface was about $\frac{1}{2}$ mm.

In a typical test, a sheet of paper was sprinkled with Xerographic toner and passed through a corona discharge. The paper, with ink uppermost was then placed on the revolving turntable, the traversing mechanism was operated by hand to produce a fused spiral. The surplus unfused ink was then removed by gentle wiping with cotton wool. A typical test sheet, with A.C. operation of the laser, is shown in Fig. 7.3.2.

7.311 Printing Tests

The first printing tests were performed with A. C. operation of the laser. The mean power was 1½ watts, but at the peak of each pulse the instantaneous power was about 8 watts. From Fig. 7.3.3 the effects of initial ink thickness may be seen. With excess ink, small ink pellets were formed which did not all adhere to the paper. With insufficient ink, the adhesion to the paper was good but the overall contrast was diminished. From the standpoint of image stability, it appears that under inking would be preferable.

Fig. 7.3.4 demonstrates the effect upon the contrast of using different kinds of paper. The gloss or art paper gave excellent results with a completely clean background. Writing or typing paper gives good contrast but the background was discoloured by trapped ink in the paper surface. This effect is even more apparent with blotting paper, there the open texture of the paper surface held sufficient unfused ink to make it appear grey.

The effect of prior electrostatic charging is shown in Fig. 7.3.5. The individual areas of fused ink are more clearly defined in the charged sample. This is discussed further in section 7.32.

To produce the printed sample shown in Fig. 7.3.6 the laser beam was chopped by a disc with a number of holes which was rotated in its path. The beam was thus modulated not only at 100 Hz from the A.C. operation of the laser, but also at a higher frequency (700 Hz in this case). Individual fused spots were produced, each with a diameter of ¼ mm.

In order to determine the effect of energy density, tests were performed with various laser powers. Filters of known optical impedance were placed in the laser beam and test sheets were produced. The energy density was calculated in terms of the peak laser power, an equivalent beam diameter and the radius on the turntable. For a given power and beam diameter, the energy density was inversely proportional to the instantaneous radius of the helix.

In Fig. 7.3.7 the width of the fused ink trace is plotted against the energy density. The circled letters correspond with those on the typical test sheet. (Fig. 7.3.2½) It may be seen that there was considerable scatter but that up to 0.02J/mm^2 , the trace width was proportional to the energy density. For higher energy density the trace width did not increase in proportion.

Also plotted on Fig. 7.3.7 are results of tests using a heat sensitive paper (Thermofax) and of tests in which typing paper was scorched. For both these the trace width was proportional to energy density. The values of energy density however were respectively 2½ and 10 times greater than those for ink fusing.

Some tests were performed with the laser operating on D. C. Fig. 7.3.5 shows trace width plotted against energy density for three kinds of paper. The laser power was 8 watts. There appears to be no significant difference in the width of trace produced. A predicted curve is also plotted, which is referred to in Section 7.42.

An additional method was examined experimentally using carbon paper. The focussed laser beam passed through a sheet of carbon paper face downwards on a sheet of plain paper. Dark particles were transferred to the paper surface. The quality of printing was poor and the energy density requirements were of the same order as those for scorching.

Poor results were obtained with Xerographic ink on polythene sheets. Better results were obtained with carbon paper placed face upwards beneath polythene, with the laser beam passing through the polythene before meeting the 'carbon'.

7.312 Pelleting Experiment in a Semi Infinite Bed of Ink

Some simple tests were performed in which pellets of fused ink were produced by allowing the laser beam to impinge upon the surface of a deep bed of ink powder.

The duration of each test was controlled by means of a shutter. The laser power was measured before each test. The pellets were weighed and the weights plotted against energy input (calculated from power x exposure time) in Fig. 7.3.9. From these results an energy requirement for fusing ink powder of 370 J/g was obtained, this is discussed in Section 7.5.

7.32 Microscopic Examination of Fused Ink

Fig. 7.3.10 shows six micro-photographs of ink spots with a linear magnification of 90. The first is from region B with normal inking. A narrow (¼mm) spot was produced, with some uncovered areas. The spot from region C, where the most acceptable visual contrast was produced, had complete ink coverage. The surface was smooth and shiny from the running together of the ink particles. The width was the nominal spot width (½mm). In region D the width had not appreciably increased, but the ink had been decomposed at the centre. The outer portions formed a continuous fused surface. The spot from region E was completely hollow, and charring of the paper in the centre had commenced; this discolouration cannot of course be seen in the photograph. The ratio of energy densities between regions E and B was about 7 to 1.

Fig. 7.3.10. 5 shows a typical underinked spot. The areas of fused ink covered only a small proportion of the spot area. The ink particles had run together into small unconnected masses. Nevertheless, some spots with good apparent contrast, were found by microscopic examination not to have full coverage of the paper by ink particles.

An undercharged spot is not reproduced but was similar to the under-inked spots in some respects. The ink particles fused into larger unconnected masses. Seen with the naked eye they produced a mottled effect, whereas the underinked spots were grey.

Fig. 7.3.10.6 shows a single spot ½mm in diameter produced by chopping the laser beam. The edges of the spot were clearly defined and the centre was well filled and shiny.

An attempt was made to view a cross section of an ink spot. The thickness of a typical spot was about 25 μm and it was noted that the paper thickness was 100 μm. This latter figure was in agreement with results of measurements using a micrometer for all papers; except blotting paper.

Some samples of ink fused onto polythene sheet were also examined. These appeared to show a certain degree of chemical bonding between the ink and polythene.

Samples of paper, without ink, which had been charred on the surface by the laser were examined. The affected areas seemed to be hardly altered when seen magnified. The discolouration could be easily removed by local abrasion e.g. eraser or sharp point. With examples of paper where ink had been fused and then removed by abrasion, it could be seen that the paper surface had been severely damaged.

7.33 Adhesion Experiments

A simple experiment was performed to determine the relative adhesion of charged and uncharged ink particles to paper. A horizontal disc mounted on a motor spindle was covered with paper and ink was sprinkled evenly on the paper. The motor was run at a number of speeds, increasing in steps. For each speed, the diameter of the circle of the ink remaining on the paper was measured.

The test was repeated using a paper disc with ink which had been subjected to a corona discharge.

The individual tests gave considerable scatter of results but the approximate ratio of adhesion forces between charged and uncharged ink was found to be 15 to 1. The importance of this is discussed in Section 7.5.

7.34 Summary of Experimental Results

1. Permanent images of good contrast were obtained by fusing powdered ink onto paper using a laser.
2. The width of fused spot produced was found to be proportional to the energy density for a range of incident powers.
3. The contrast of fused images was enhanced by prior electrostatic charging of the ink.
4. Inferior images were produced using heat sensitive (Thermofax) paper, the energy density required being $2\frac{1}{2}$ times greater than for ink fusing.
5. Ten times the energy density for fusing was found to be required for scorching paper.

7.4 Theory of Image Formation by Fusing Ink Onto Paper

The images formed by this printing process owe their existance to the retention of discrete areas of ink particles on the surface of paper. The ink particles are approximately spherical and 5 to 10 µm in diameter. The plastic resin, which is their main constituent, melts at 336 K and starts to decompose at 431 K. The paper surface although microscopically smooth, consists of partially loose fibres a few µm in diameter.

To form an image the ink particles must bond together and also to the fibres of the paper surface. The surrounding area must remain essentially free from ink particles after the brushing process. The thickness of the fused ink is not important so long as the covering in the required area is continuous, since the ink particles are entirely opaque in the visible regions. The temperature of the ink should not be raised above 431K.

7.41 Postulated Mechanism of Fusing

For satisfactory fusing to occur, the ink in direct contact with the paper must be melted. Heat must therefore, be supplied which raises the temperature of the ink, and part of the paper, from ambient to above 336K and to melt the ink. In addition, there must be an attraction between the ink and the paper. The forces of surface tension on the ink particles as they melt will not promote adhesion.

The electrostatic forces overcome any tendency for the particles to agglomerate and instead a minimum energy level is achieved by the particles drawing closer to the paper.

7.42 Energy Considerations Lumped Systems

For this treatment of the problem, it is assumed that the rate of heat transfer, within the ink and paper, is not important. Only the heat energy entering the system and the thermal capacities are relevant.

Consider first the case of the pelleting tests (Section 7.312) where there was no paper. The laser beam impinged on the ink for a short time, the energy given to the ink was:-

$$Q = W_1 te \qquad (1)\ *$$

A pellet was produced, when the temperature of the ink rose from θ_a the ambient temperature to temperature θ. Since melting must have taken place to produce the adhesion $\theta > \theta m$ and energy must have been supplied to satisfy the latent heat hence:-

$$Q = M\left[C_i\ (\theta - \theta_a) + L_{mi}\right] \qquad (2)$$

Tests on the ink had shown that it degrades at a temperature θ_d . Above this temperature, any further energy causes the ink to break down into gaseous form.

* Symbols are listed on Page ix

Since the emissivity of ink is nearly unity (0.96) - see Section 10.5, it is ignored in subsequent calculations.

If it is assumed that the temperature was raised in the pelleting tests to θ_d then equation (2) becomes:-

$$Q = M\left[C_i(\theta_d - \theta_a) + L_{mi}\right] \qquad (2')$$

Taking values of properties from Appendix Section 10.5 and assuming a mean ambient temperature of 288K.

$$Q = M\left[1.7\ (431 - 288) + 1.3\right] = 245\ M$$

or $\quad Q/M = 245$ J/g

A line of Q/M = 245J/g is drawn on Fig. 7.3.9 which shows the experimental results of the pelleting tests. Also drawn is Q/M = 370J/g which represents 150% of the energy previously calculated. These results are related in Section 7.5.

This method can now be extended to the practical region where the ink is on top of paper. Consider an area of ink on paper receiving an amount of heat Q. The mass in equation (2) is replaced by terms for ink and paper including density. Thus equation (2) becomes:-

$$Q = A\left[Z_i w_i L_{mi} + (\theta - \theta_a)(Z_i w_i C_i + Z_p w_p C_p)\right] \qquad (3)$$

For a moving energy source of effective width Y_1 with a velocity relative to the ink of V_1 we can write an Energy density term:-

$$E = \frac{Q}{A} = \frac{W_1 t}{Y_1 V_1 t} = \frac{W_1}{Y_1 V_1} \qquad (4)$$

This is true even for a circular spot of effective diameter Y_1 if $V_1.t \gg Y_1$.

We must distinguish between the effective beam spot width Y_1 and the width of fused ink spot produced Y_i. Equation (3) may be rewritten in terms of Y_i :-

$$Q = Y_i V_1 t \left[Z_i w_i L_{im} + (\theta - \theta_a)(Z_i w_i C_i + Z_p w_p C_p) \right] \qquad (5)$$

but $Q = W_1\ t$ (equation (1))

$$W_1 t = Y_i V_1 t \left[\ldots\ldots \right]$$

$$W_1 = Y_i V_1 \left[\ldots\ldots \right]$$

$$\frac{W_1}{Y_1 V_1} = \frac{Y_i}{Y_1} \left[\ldots\ldots \right]$$

Hence from (4) $E = \frac{Y_i}{Y_1} \left[\ldots\ldots \right]$

$$\therefore Y_i = \frac{E Y_1}{\left[Z_i w_i L_{im} + (\theta - \theta_a)\ (Z_i w_i C_i + Z_p w_p C_p) \right]} \qquad (6)$$

This may be evaluated using the values properties in Appendix Section 10.5 and values of Y_1, Z_i, and Z_p from Section 7.32 again assume that $\theta = \theta_d$ and that the whole thickness of the paper is heated.

Hence $Y_i = 26.5\ E$ mm, where E is in J/mm^2

This line is plotted with the experimental fusing results on Fig. 7.3.7 and Fig. 7.3.8.

7.43 One Dimensional Heat Transfer with Stationary Heat Source

If we consider a stationary heat source at the surface of the ink with a power of w acting for a time t on an area A, giving a heat flux F=W/A we may determine the temperature at any depth. We consider only locations along the axis of the heat source (direction z perpendicular to the paper surface). For simplicity the ink and paper are taken as a single homogeneous semi-infinite slab. We also assume that no significant heat is used to produce phase change in the ink. Carslaw and Jaeger (7/5) (p. 75) give this expression for the temperature rise:-

$$\Delta\theta = \frac{2F}{k}\left[\left(\frac{Dt}{\pi}\right)^{\frac{1}{2}} e^{-\frac{z^2}{4Dt}} - \frac{z}{2}\,\mathrm{erfc}\left(\frac{z}{2(Dt)^{\frac{1}{2}}}\right)\right] \qquad (7)$$

where k and D are the thermal conductivity and diffusivity and 'erfc' is the complementary error function defined and tabulated on p. 485 of Carslaw and Jaeger (7/5).

This equation has been evaluated using material properties from Appendix Section 10.5 for a value of F which has been shown experimentally to give good fusing (22 watts/mm^2 for 0.001 seconds). This results in a maximum surface temperature of 1800K and an interface temperature of 400K (i.e. at Z = 0.025mm).

7.44 Three Dimensional Heat Transfer with Stationary Heat Source

The treatment used in the previous section is here extended to include the transmission of heat in the plane of the paper. The mean beam radius r is used and the temperature rise along the axis is given by Carslaw and Jaeger (7/5) on page 264 as :-

$$\Delta\theta = \frac{2W}{\pi r^2 k}(Dt)^{\frac{1}{2}}\left[ierf\left\{\frac{Z}{2(Dt)^{\frac{1}{2}}}\right\} - ierfc\left\{\frac{(Z^2+r^2)^{\frac{1}{2}}}{2(Dt)^{1/2}}\right\}\right] \tag{8}$$

this assumes a uniform energy distribution across the beam, but Guenot and Racient (7/6) have shown that this does not
a
effect temperatures along the axis.

Using the same values as in Section 7.43 equation (8) has been evaluated. For this ratio of Z to r and with the small value of t, the temperatures are the same as from equation (7) in Section 7.43. The effect of transverse heat transmission would only be significant for smaller values of r and much larger values of t.

7.45 Statement of Full Problem in Three Dimensional Transient Heat Transfer

The aim of this Section is to outline the full heat transfer problem and to point to some possible approaches towards a solution.

What is required to be known is the temperature distribution, in all three coordinates, in a system consisting of a layer of ink on a layer of paper. The surface of the ink is subjected to a moving radiant heat source, the power of which varies with time. The energy distribution across the beam is not known and may not remain the same for different total powers of the beam.

The ink layer is composed of particles which are not all of the same size and shape. The emmisivity of the ink surface as a whole is not known. The energy absorbtion of the ink particles at the particular wavelength of the laser beam is not known. Probably the ink particles transmit some of the heat and absorb some of the heat. This would have the effect of heat generation within the ink layer as non-linear function with respect to depth. It should not be assumed that the ink layer is either homogeneous or isotropic with respect to thermal conductivity.

The ink particles suffer a change of state during the heating process. This has two effects; first to absorb more heat without change of temperature thus spoiling the heat transmission equation, second the geometry of the system changes as the particles melt together. This change of geometry will have an effect on the conductivity of the ink. If the degradation temperature is reached energy will be absorbed and ablation will occur.

At the ink/paper interface the conductivity will depend upon the surface texture of the paper. If some energy is present in the form of radiation, having not been fully absorbed by the ink, the emmisivity will be involved. For thin paper, the temperature and thermal capacity of the substrate will have some effect.

Taking these problems in order, possible methods of attack may be mentioned. van Nood and Beek (7/7) treat the case of radiative heat transfer to a moving plate, but the material involved has high conductivity and the irradiated area is large compared with the strip width. Cobble (7/8) considers the heating produced by a moving discrete source and presents a finite transform solution. This approach might prove useful if suitable property values could be found, since it takes account of losses at the boundaries. Carslaw and Jaeger (7/5) give an analytical solution for a slab on p.268. This is rather formidable even for a semi-infinite homogeneous medium. The question of energy distribution within the beam is considered by Guernot and Racinet, (7/6); the axial temperatures are not effected, but off-axis temperatures are. They give expressions for the off-axis temperature distribution for a Gaussian energy distribution within the beam.

The heat conduction problems associated with porous media are discussed by Luikov et al. (7/9). They consider how the overall heat transmission by packed particles may be evaluated but do not consider heat generation within the particles. Cline and Kropschot (7/10) consider the same problem and also include mixtures of powders.

Brodie and Mate treat the same problem but in conditions where radiation between the particles is not significant (7/11). Van den Held (7/12) derives some complex mathematical expressions relating to conduction in materials where radiation is also important, i.e. semi-transparent media.

The matter of change of state is considered by Murray and Landis (7/13) is one dimensional and an outline is given of a method of solution applicable to digital and analogue computation. Goodman (7/14) presents an approach to the one dimensional problem which employs the Heat Balance Integral. Lockwood (7/15) gives a numerical procedure for digital computer solution of the problem in three dimensions. Boley (7/16) (7/17) considers the cases where there is not only a change of state but where ablation also occurs. Penner and Sharma (7/18) give an analytical expression for the one dimensional case of absorbtion within an irradiated medium with ablation at the surface.

A probability approach to the solution of transient heat conduction problem is given by Haji Sheikh and Sparrow (7/19). They claim that their "floating random walk" approach may be applied to a wide range of problems. A perturbation solution is suggested by Kicker and Asnani (7/20) but this appears to be only applicable to isotropic homogeneous media. The electrical analogue method of solution is outlined by Liebmann(7/21) (7/22). He claims that it is applicable to problems including change of state.

It may be seen from this short review that most of the aspects of the problem can be tackled individually. Either fairly complex analytical solutions or sophisticated numerical methods may be found to treat the individual parts. Nevertheless to combine all these to give a complete theoretical picture of the problem is a task which does not seem to be justified, particularly since the physical properties of the materials involved are so ill defined.

7.5 Correlation between Experimental Findings and Theoretical Predictions

In Section 7.42 consideration was given to the fusing of powdered ink, in a deep bed, into pellets. Using the assumed properties of the ink, a relationship was obtained between the incident energy and the pellet mass produced. This is compared with the experimental results in Fig. 7.3.9 It may be seen that there is good correspondence between the theoretical prediction which allows an extra arbitrary 50% for losses and the experimental values. The losses would include energy causing degradation at the upper ink surface and energy given to adjacent ink particles which was insufficient to cause fusing. Bearing in mind the uncertainty associated with the property values, this degree of agreement must be considered satisfactory.

In the analysis of the printing tests, it was assumed that no energy was used to heat the unfused ink particles. It was also assumed that the whole paper thickness was raised to the same temperature as the ink whereas the lower surface probably did not in fact reach this state. It was thought reasonable to allow one of these effects to cancel out the other.

The simple relationship between energy density and spot width was plotted with the experimental results in Figures 7.3.7 and 7.3.8. In regions A B and C, where microscopic examination had shown good fusing without degradation, there was good agreement between theory and experiments.

Allowing for experimental scatter, this is true for A. C. and D. C. operation, for three kinds of paper and over a four to one range of incident powers. When considering the degree of scatter, it must be remembered that the initial ink layer thickness was not closely controlled.

It can clearly be seen that for regions D and E, where energy was being used to degrade the ink, the spot width was not proportional to the energy density. In the cases of the marking of Thermofax paper and the scorching of paper a direct proportionality again applied. No theoretical prediction of the constant was made.

The theoretical predictions of temperature distribution based on one and three dimensional heat transfer were not realistic (Sections 7.42 and 7.44). The surface predicted temperatures would have caused degradation, signs of which were not observed microscopically. The explanation lies in the nature of the ink. It was not a homogeneous solid medium receiving heat only at the surface. Its particles transmitted part and absorbed part of the incident radiation by a scattering process. This effectively caused heating within the ink layer. This had the effect of flattening out the steep temperature gradient.

Since these simple approaches to the solution of the heat transfer problem yielded such disappointing results, the full treatment mentioned in Section 7.45 did not seem to justify further consideration.

7.6 Conclusions

It has been shown that images of good optical quality may be obtained by using a laser. The best images were obtained by fusing powdered ink onto paper. Less energy was required for this than for scorching paper or marking a heat sensitive paper.

The experimental results relating energy density and spot size were in good agreement with the predictions from a simple theory. It appeared that an approach using internal heat transfer was not justified. Although the full theoretical problem was outlined, no attempt was made to formulate a complete theory for the complex problem.

Printing by this means appeared to be possible on a wide range of papers and some other materials.

The laser size required for printing at the design speed would depend upon the control system employed. A prediction using the simple lumped system approach is a mean power of 500 watts. This is well within the power range now available.

7.7 Suggestions for Further Work

The following avenues for further work should be considered:-

1. Tests with finer inter-line spacing to determine the effects of heat flow at right angles to the direction of scan. These could reveal a limitation of the process particularly for half tone work.

2. Tests with higher powers and speeds to ensure that the energy density criterion is true for speeds at which commercial printers might work.

3. More detailed examination of the available beam modulation techniques, and of possible mechanisms for use in a system employing variable speed scanning. This latter is an elegant solution to the modulation problem but at present would require a mechanical deflection system. Electro-optic deflecters, which already exist for shorter wavelengths, may become available. (7/23)(7/24) (7/25) (7/26) (7/27) (7/28) (7/29).

4. The process of surplus ink removal by suction or air knifing, with or without the application of an alternating electrostatic field.

5. The printing by means of a laser on surfaces other than paper should be studied. Printing onto transparent plastic films was tried with varied success in the course of this present work. A systematic study, bearing in mind the chemical properties of both ink and sheet materials, would be most rewarding.

6. A further study of laser progress with particular reference to leasers working in the near infra red (about 1 µm wavelength). Such high powered solid state lasers e.g. Ho in YAG, are thought to have been made. This would be particularly good because glass optics could be used and electro-optic modulators work already in this region.

8.0 Overall Conclusions

1. It has been shown that lines of alpha-numeric characters may be printed Xerographically at speeds in excess of 5,000 lines per minute. The optical characters used were of a brightness (60 lux) obtainable from a cathode ray tube.

2. Aerosol development has been proved to be a viable development method at linear speeds in excess of 0.5m/sec. Positive (black on white) and negative (white on black) printing have been demonstrated.

3. Some half tone images have been printed using aerosol development at speeds of 0.1 m/sec.

4. The transfer of images to paper at speeds above 0.5 m/sec has been demonstrated.

5. Printed characters have been produced of reasonable optical contrast (considering the physical state of the selenium coated plates).

6. Visible images fixed on paper have been produced using a laser.

7. The method of fusing ink particles has been shown to require a lower energy density than other laser printing techniques.

8. The optical contrast of the fused images has been demonstrated to be very good using a wide range of types of paper.

9. The estimated laser power requirement for a high speed printer is within the range of lasers available (c. 500 watts).

10. The resolution obtainable (4 lines/mm) is suitable for characters and for some kinds of half tone printing.

8.1 Recommendations

1. That further work, on an individual basis, is not justified towards improving the Xerographic printer.

2. That in the light of the results of the laser printing work, further efforts in this direction should be made. The particular areas in which fruitful studies might be pursued are:-

i. Laser beam modulation and scanning methods with particular reference to variable velocity scanning.

ii. Powder handling techniques related ot the production of thin even layers.

iii. Intermittant paper feed mechanisms to operate at high speeds.

iv. Systems for the removal of surplus powder and its re-use.

v. The relationship between laser power and printing speed with higher powers, together with the effects of scan spacing.

9.0 Acknowledgements

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For the supply of wire samples, the author wishes to express his indebtedness to the Mullard Co. Ltd., Blackburn.

10 Appendices

10.1 Units and Standards

The work described here was commenced in 1963 before the Government's announcement of the change to the Metric (Sl) system of Units (24th May, 1965) The initial calculations and apparatus design were performed using Imperial Units. Wherever possible these figures have now been converted to S.l. units in this thesis. The latter part of the work was pursued throughout using S.l. units.

B. S. 3763 1964 has been used for the values of the units and in general the names used are the same. However, some temperatures are quoted in Celcius for ease of understanding. Also the I.S.O. approved unit hertz (Hz) is used for frequency.

10.2 Calibration Tests

The following sections describe the calibration tests performed for both the Xerographic and laser printing projects. The calibration curves form the first part of Section 11.

10.21 Calibration of Belt Speed

The main parallel cotton belts were run at a number of speeds up to 150% design speed. At each point the Servomex control indicated speed was plotted against the belt speed measured with a hand held tachometer (Fig. A). From this, Fig. B was drawn which relates printing speed (lines/sec) to the indicated motor speed.

10.22 Characteristics of EHT Supply Charging Unit.

The electrostatic voltmeter had a 0-6kV movement but voltages of 12 kV were to be measured. A 200 MΩ resistive divider was mounted within the meter case. The meter was calibrated using a 10 kV English Electric Insulation tester Fig. C shows the calibration curve.

The EHT Unit output was controlled by a potentionmeter which varied the grid voltage of the oscillator valve. A series of current v. voltage readings were obtained for different settings of this potentiometer. A resistive load was used. These results were not found to be very repeatable due to instability of the oscillator and breakdown of the ammeter. It was decided to use only dynamic characteristics obtained with discharges to a moving plate as described in Section 5.31. Charging currents are plotted against open circuit voltage from these dynamic tests in

Fig. D (positive wire potential) and Fig. E (negative).

10.23 Illumination Levels

The illumination along the exposure slit was measured for three settings of lens aperture. A cadmium sulphide photo-cell was used, which had been calibrated against an Ilford SE 1 photometer. Fig. F shows the results graphically. The illumination was found to vary along the slit and was very sensitive to the rotational location of the lamp filament. The maximum illumination, at the centre, was about 60 lux with the lens unstopped (f/2.9).

10.24 Laser Output Power

The apparatus described in Section 7.26 was used to measure the output power of the laser with A.C. and D. C. operation. The copper calorimeter was positioned directly in the beam close to the end of the laser tube. An asbestos shutter was interposed except during exposures.

The thermocouples was calibrated against a mercury in glass thermometer in a water bath. For each power measurement, the calorimeter was exposed for sufficinet time to allow the temperature to rise 20-30°C. A trace of temperature time was obtained which included the cooling curve obtained when the shutter had been replaced. The net power was computed from the heating gradient added to the cooling gradient.

For A. C. operation, the electrical input was not varied but the tube pressure was altered over a wide range. Fig. H shows the relationship between laser output power current and tube pressure. An efficiency curve is also given calculated from the input power, (Fig. G) and the measured output.

The means employed for the measurement of output was most unlikely to give high readings and therefore the power curve was drawn through the highest experimental points. Points falling below this line were considered to be due to imperfect laser mirror alignment.

These tests suggested that maximum efficiency (3%) and power ($6\frac{1}{2}$ watts) could be obtained with a tube pressure of about 10 torr and a current of 35 mA.

For D. C. operation, the tube pressure was held at a value of 10 torr and the electrical input varied. Fig. I shows the relationship between tube voltage and current, and also between power and current. Fig. J shows the relationship between output power and current. A maximum power of 9 watts was obtained with a current of 70 mA. Due to the electrical instability of the system at low currents, few experimental points were obtained below 50 mA. The curve of efficiency against current shows no clear maximum.

10.3 Laser Hazards and Safety Notes

10.31 Notes based on Personal Experience

The CO_2 laser works at a wavelength of 10.6 μm, and does not produce directly any radiation in the visible region. Glass, water and the cornea of the eye do not permit the transmission of this wavelength. There is however danger of physiological damage by direct burning of any part of the body. The laser beam is of sufficient intensity to cause burns even when unfocussed. If burning occurs on the skin, pain is immediate and the normal reflex action reduces the danger by removing the affected part from the beam by muscular action. The fingernails however present a greater hazard since the beam penetrates the nail and starts to burn without immediate pain being felt.

From the forgoing it will be realized that every precaution must be taken to prevent the laser beam from impinging on any part of the person.

The direct fire hazard must also be noted. The energy concentration in the unfocussed beam is sufficient to inflame paper, cardboard, wood etc., in a matter of seconds. Firebricks or thick asbestos must be used in the line of the beam. ¼" thick Perspex sheeting is useful to shield the apparatus in case of stray radiation. This can be penetrated by the beam but it takes time and the smell is distinctive.

It should be noted that all metals, even if unpolished, are good reflectors at this wavelength thus stray reflections of consideration intensity can easily occur if the beam impinges on metal.

Damage can occur to the eyes from secondary emissions in the visible region when the focussed beam impinges on a non-reflecting object. The light thus emitted by nearly all substances is very intense and protective glasses should be worn.

Probably the most serious hazard is the electrical power supply; on D. C., 12 kV can be across the electrodes with ½ A capacity. This will kill anyone who comes in contact with the live terminal and earth.

10.311 Simple Rules based on Personal Experience

1. Never look into the laser tube unless the power supply is switched off and you have taken the key out.

2. Never switch the laser on with the covers removed; The power supply is lethal.

3. Check for metal objects which could cause stray reflections before switching on.

10.32 Laser Safety Notes from S.E.R.L.

MINISTRY OF DEFENCE
SERVICES ELECTRONICS RESEARCH LABORATORY
BALDOCK, Herts.
Telephone: Baldock 3351, *ext.*

Reply to Superintendent quoting: 356/68/IPDG/ABJS
Your reference:

18th June, 1968

Mr. P. J. Watson,
Department of Mechanical Engineering,
University of Technology,
Loughborough,
Leics.

Dear Mr. Watson,

I enclose a copy of some CO_2 laser safety notes prepared by our establishment laser safety officer. These are intended for guidance to staff at S.E.R.L. and, while I hope they will be useful to you, we cannot accept any responsibility for their use in safety recommendations outside S.E.R.L.

Yours sincerely,

A B J Sullivan

(A. B. J. Sullivan)

MINISTRY OF TECHNOLOGY

SAFETY SERVICES ORGANISATION

Safety Memorandum 67/67

The Carbon Dioxide Laser

The Ministry of Aviation Code of Practice on laser systems deals with those laser wavelengths which are transmitted by the eye to the retina.

Since the eye is opaque to radiation from the carbon dioxide laser, different safety criteria are needed.

No such criteria being available at the present time, the following information is offered as guidance.

It has been established that 6 joules/sq.cm. delivered in 0.5 second will produce a first degree burn on the cornea.

For continuous radiation, 100 milliwatts/cm^2 has been said to be a threshold of damage.

It is reasonable therefore to consider 10 milliwatts/cm^2 as a safe working level for continuous radiation. This figure is also accepted for microwave radiation incident on the eye.

This information is transitional until experimental work being done in the United Kingdom is complete, when the results will be incorporated in a revised edition of the Code of Practice.

S.S.O.,
Room 607,
Station Square House,
St. Mary Cray,
ORPINGTON, Kent.
17/5/67

(B.A. WESTON)
Chief Safety Officer

F.205927.

SAFETY PRECAUTIONS FOR THE OPERATION OF LASERS OF THE CARBON DIOXIDE TYPE

The introduction of high-power long-wave infra-red lasers of the carbon dioxide type presents a serious hazard to the safety of operators and bystanders. It is essential that rigorous safety precautions are imposed when such equipment is operated.

The nature of the hazard is somewhat different from that which had previously been experienced. Radiation of wavelength greater than about 1.5 μ will not penetrate watery body tissues more than a very short distance, so that danger of focussed radiation damaging the retina of the eye is virtually absent. However there remains the direct surface heating effect of the high density radiation which can not only burn the skin, clothes etc., but is particularly dangerous to the front surface of the eye lens, or cornea.

Little accurate work has yet been published on the effects of high density infra-red radiation on body tissues. However the following damage levels have been reported, and they give some idea of the possible danger.

1/100 watt/sq.cm. ~~Recommended maximum furnace working level.~~ Recommended maximum laser radiation level at eye

3 watts/sq.cm for about 1 sec - almost always gives immediate mouse skin lesion.

6 watts/sq.cm for 2 secs - gives corneal cataract.

13-25 watts/sq.cm for < 1 sec - gives 3rd degree burn on skin.

15 watts/sq.cm for 1 sec - causes dense white corneal opacity.

50 watts/sq.cm - cornea perforated.

carbon dioxide laser Safety

Recommended safety levels and procedures

Since the danger is that of heating, and in the absence of more detailed investigations of any other effects of long-wave infra-red radiation, it is proposed that the maximum furnace working level of 1/100 watt/sq.cm be taken as the maximum permissible for the naked eye. The maximum permissible laser radiation level on the unprotected skin has already been set at 1/10 watt in any square centimetre in any one second period. There is therefore a factor of ten between the two cases. This means that the wearing of I.R. opaque enclosing goggles will protect the eye in the presence of limiting skin radiation intensity. Furthermore, so long as the goggles are non-splinter and adequately refractory, some measure of protection would be given against accidental exposure to more intense radiation by allowing time for evasive action.

All high-power long-wave infra-red equipment and beam paths should be enclosed within electrically interlocked non-transmitting screens.

Access to working regions, where absolutely necessary, should be made through self-closing hinged panels set well below eye level. Particular care should be taken to maintain in position suitable refractory, non-reflecting beam terminators. It should be noted that the reflectivity of an otherwise poorly-reflecting matt surface can be greatly increased if the incident energy causes local melting.

To extend the "Recommended laser safety thresholds" list to cover the long wave infra-red case, existing copies of the undated original note "Safety Precautions for the Operation of Laser Equipment" should be destroyed, and replaced by the February 1968 issue attached herewith.

P.G.R.King.

Establishment Laser Safety Adviser.

7th February, 1968

S.E.R.L.,
Baldock,
Herts.

SAFETY PRECAUTIONS FOR THE OPERATION OF LASER EQUIPMENT

General notes and comments

Advice on laser safety precautions will normally be the responsibility of the Group Safety Officer[1]. When necessary, he can consult the Establishment Laser Safety Adviser.

All Group Safety Officers and preferably all those directly engaged on laser development should read the Ministry of Aviation Code of Practice.

Periodic ophthalmological inspections should be carried out as recommended in the MoACoP.

While the wearing of protective glasses can introduce risk on its own account (by causing the eye to become dark adapted, by limited waveband rejection, by engendering a false sense of security etc.) there are undoubtedly cases where they should be used, as for instance by using plain glass goggles in the presence of long wave infra-red and/or U.V.

---

[1] This arrangement saves increasing the number of Safety Officers, and facilitates easy co-ordination of Electrical and Laser safety precautions.

SAFETY PRECAUTIONS FOR THE OPERATION OF LASER EQUIPMENT

The following precautions are proposed as a common basis for the advice to be given to Group Leaders, who are responsible for the safe use of laser equipments in their group.

In all cases, the officer responsible for setting up new laser equipment, or modifying existing equipment, should consult the Group Safety Officer and agree on the safety measures to be taken. The Establishment Laser Safety Adviser can be consulted if necessary.

It must be emphasized that the electrical side of laser apparatus can be more dangerous than the laser radiation, so that the Electrical Safety Code of Practice must also be observed in all cases.

Laser systems which can produce radiation levels greater than those specified in the current Laser Safety Threshold Recommendations (see Appendix) should in all possible cases be confined within an enclosure such that no hazardous radiation can emerge. The nature of this enclosure may range from securely fixed or electrically interlocked screening to an entire laboratory. In the latter type of case, except in the special circumstances discussed below, no person shall remain within the enclosure while the laser is operating. All such laser protection enclosures must carry a prominent notice reading: LASER EQUIPMENT. OBSERVE 'DANGEROUS LASER' SAFETY PRECAUTIONS BEFORE OPENING.

Circumstances may arise which make it impossible to screen off completely from an operator or observer certain dangerous laser apparatus, as for example when adjustments or observations must be made to an experimental laser, or one which is normally confined within a safety enclosure. All systems and circumstances of this nature will be classified 'DANGEROUS LASER' and the following precautions shall be taken.

'DANGEROUS LASER' Safety Precautions

Access to dangerous laser radiation must be denied to other members of the laboratory, visitors, and members of the general public by means of a sufficiently robust and opaque enclosure or by the erection of barriers at the limits of the dangerous irradiation area.

Where the enclosure can be entered, the entrances to the hazardous regions must be fitted with interlocks such that it is not possible to operate the laser if the entrances are open. After such an interlock has been broken and remade, it must not be possible to operate the laser without operating a manual reset at the control point. If the laser is normally operated from outside the enclosure then a changeover switch must be fitted to allow any operator within the enclosure to assume overall control. Isolating switches must be easily accesible to any position within the enclosure.

Adequate warning must be given by the operator to others within the enclosure that the laser is about to be switched on, a sufficient interval being allowed for anyone within the enclosure to reach an isolating switch if necessary. When any dangerous laser is operating within a safety enclosure capable of being entered, there shall be an illuminated sign at all entrances to the enclosure worded DANGER - LASER ON.

All staff working in Dangerous Laser areas are to be adequately trained and experienced or supervised until they acquire the necessary knowledge and experience. Industrial staff may not enter a Dangerous Laser area while any of the warning signs are on.

Where dangerous radiation has to be propagated outside the laboratory and all the foregoing precautions cannot be applied, then the officer in charge of the equipment must ensure that the possible irradiated area does not include any ground on which the public might venture and/or ensure by good discipline and a sound drill that the laser system is not operated when members of the public are in the potentially hazardous area. Appropriate safety precautions shall of course still be observed within the laboratory.

APPENDIX

PROCEDURE FOR ASSESSING LASER RISK TO THE EYE

SYMBOLS

Let	energy entering pupil	= j joules
	energy density at retina	= E_r joules/cm^2
	power entering pupil	= w watts
	power emitted from laser	= w_1 watts
	pulse length	= t secs
	diameter of retinal image	= i cms
	diameter of pupil	= d cms
	diameter of laser beam incident on the eye	= l cms
	diameter of laser spot on target	= I cms
	distance of target from eye	= R cms
	focal length of eye	= F cms (= 1.7cms)
	beam divergence	= ω rads

CALCULATION OF RETINAL IMAGE DIAMETER

Choose the largest value from the following possibilities:

(a) Geometrical imaging

Diffuse reflection from an illuminated target diameter I cms at range R cms

$$i = 1.7\ I/R$$

(b) Direct incidence of solid state laser beam

If the basic divergence of the beam is ω,

$$i = 1.7\omega$$

(c) Image limited by diffraction at the pupil

If the pupil is fully illuminated with direct or scattered laser radiation and its diameter is d in cms, then, if the wavelength is λ_μ in microns

$$i = 2.35 \times 10^{-4}\lambda_\mu/d$$

(d varies from 2 mm to 6 mm, depending on whether the eye is light- or dark-adapted)

(d) Image limited by diffraction in the laser beam itself

If the diameter of the laser beam passing through the pupil is 1 in cms ($1 < d$), then if the wavelength is $\lambda\mu$ in microns

$$i = 2.35 \times 10^{-4} \lambda\mu / 1$$

(e) Eye resolution

$$i = 8 \times 10^{-4} \text{ cms}$$

CALCULATION OF EFFECTIVE RADIATION

(a) Direct laser beam, smaller than pupil.

All radiation effective.

$$E_r = 4j/\pi d^2 \text{ joules/cm}^2$$

$$W = W_1 \text{ watts}$$

(b) Direct laser beam of diameter 1 ($> d$)

Incident energy at pupil modified by approx. $d^2/1^2$

(c) Diffuse reflection from an illuminated target.

$$j = j_1 d^2/4R^2$$

$$W = W_1 d^2/4R^2$$

EVALUATION OF RISK

If irradiation time is less than 0.1 sec, calculate joules/cm^2 in the retinal image and check if this is greater than the recommended threshold for that particular irradiation time.

If the irradiation time is greater than 0.1 sec, calculate the watts in the retinal image, and check that this is not greater than the recommended threshold.

If the irradiation consists of a train of high repetition rate pulses, check that neither (a) a single one of those pulses nor (b) the time averaged watts in the retinal image over a period of 0.1 secs exceeds the recommended values.

RECOMMENDED LASER SAFETY THRESHOLDS JUNE 1965

Pulse length	Safety Threshold (E_r)
1 - 1000 mS	1 mJ/cm^2 in the retinal image
1 - 1000 μS	10 mJ/cm^2 in the retinal image
1 - 100 nS	100 mJ/cm^2 in the retinal image

Alternatively the following relationship may be used: $E_r = \sqrt[8]{t}$

0.1 sec - C.W.	100 μW into the retinal image (If the retinal image diameter is known to lie between 1/25 mm and 3½ mm, 1 mW should be acceptable)

On any part of the body other than the eye, the total laser energy incident during any period of 1 second should not exceed 0.1 joules on any square centimetre regardless of how the energy is distributed or concentrated within that square centimetre.

For radiation of wavelength greater than 1.5 μ, average power density incident on the eye must not exceed 10 mW/sq.cm.

S.E.R.L.,
Baldock,
Herts.

February, 1968.

10.4 Laser Operating Procedure

10.41 A.C. Operation

1. Connect main laser electrodes to output terminals of 10 kV transformer, ensuring that neither electrode is earthed.
2. Connect A. C. ammeter (100 mA) between central terminals of output winding of transformer.
3. Connect 12 kV voltmeter across laser electrodes.
4. Close gas cylinder valve (See Fig. 7.2.5)
5. Switch on vacuum pump.
6. Connect vacuum pump inlet to laser outlet valve, open laser inlet valve, open laser inlet needle valve.
7. Allow system to pump down to below 1 torr pressure.
8. Close laser outlet valve. Close needle valve.
9. Open gas cylinder valve and open regulator to about one division.
10. Open needle valve 10 divisions.
11. Allow pressure to rise to 20 torr.
12. Open laser outlet valve about $\frac{1}{4}$ turn.
13. Turn on cooling water and ensure that there is a moderate flow through tube jacket and electrode pipe.
14. Switch on 240 volt A. C. supply to 10 kV transformer.
15. Adjust laser outlet valve to give steady tube pressure of 10 torr.
16. Allow 10 minutes for laser to warm up before making adjustments to mirrors to obtain maximum output.

10.42 D.C. Operation

1. Connect R. H. laser electrode to live output from EHT unit via 15k Ω resistor (see Fig. 7.2.6)

2. Connect L. H. laser electrode via ammeter and trip relay R3 to earth.

3. Connect 12kV voltmeter across laser electrodes.

4. - 13. :- as for AC operation.

14. Close needle valve and allow pressure to fall to 6 torr.

15. Turn variac to zero.

16. Switch on main switch (L.H. side of control panel)

17. Turn on Key switch.

18. Press start button.

19. Increase variac setting until gas in tube conducts.

20. Reduce variac setting to keep current below 120 mA.

21. Open needle valve 10 divisions.

22. Allow pressure to rise to 10 torr, using variac to maintain constant current of 90-120 mA.

23. Adjust laser outlet valve to give steady pressure of 10 torr.

24. Allow 15 minutes before adjusting mirrors to obtain maximum output.

10.43 Shutting Down Procedure

1. Switch off electricity supply to laser tube (press STOP button on D.C.).

2. Shut all gas cylinder valves.

3. Switch off vacuum pump and disconnect inlet pipe.

4. Turn off cooling water.

10.44 Mirror Alignment.

1. Pump down laser tube to 10 torr or below.

2. Check that electricity supplies to laser tube are off and cannot be re-connected by accident.

3. Remove laser tube cover.

4. Arrange bright light to shine on R. H. end of laser tube towards mirror.

5. Slacken off all mirror adjusting screws so that mirrors are held on their 'O' rings by vacuum only.

6. Look through window at L. H. end and adjust solid mirror at R. H. end by screwing in adjusting screws until a symmetrical reflection is seen; the window should appear as a black dot in the centre of the mirror.

7. Adjust to L. H. mirror by screwing in the adjusting screws until the inside of the tube appears as a series of concentric circles.

8. Replace tube cover.

N. B. If the laser does not lase immediately when switched on after static mirror alignment, it should be switched off and the procedure repeated.

10.5 Properties of Ink and Paper

The ink used for both parts of the work was Xerographic Toner manufactured for use in the copying machines of Rank Xerox Ltd. The manufacturers were unable to supply details of the physical properties of the ink. They did however say that it was covered by British Patent No. 893,332 (1958). This describes a toner consisting of a resin mixed with carbon black with a particle size range between 1μm and 20μm. From this specification it did not seem to be possible to assign absolute values of physical properties to the ink in question. Some tests were therefore performed to discover some properties.

Particle size analysis revealed a size range from 5 to 10 μm. Differential thermal analysis gave a melting point of 336K, a heat of fusion of 1.3 J/g and 431K as the temperature at which degradation commenced. Samples of paper were weighed and measured to determine density.

From a literature survey of the thermal properties of paper and various plastics, values were assumed for the properties which are tabulated on page 101

Assumed Properties of Ink and Paper

Property	Symbol	Units	Ink	Paper
Density	w	g/mm^3	1.3×10^{-3}	0.8×10^{-3}
Specific Heat	C	J/gK	1.7	1.3
Thermal Conductivity	K	W/mmK	$100 - 300 \times 10^{-6}$	100×10^{-6}
Thermal Diffusivity	D	mm^2/5	$45 - 140 \times 10^{-3}$	100×10^{-3}
Latent Heat (Fusion)	L	J/g	1.3	-
Melting Temperature	Om	K	336	-
Degradation Temperature	Od	K	431	-
Emissivity (.4μm)	e	-	0.97	0.34
Emissivity (10μm)	e	-	0.96	0.96
Layer Thickness	Z	mm	0.025	0.1

Cost of Consumables for different Printing Processes

The costs quoted are in pence per square metre of printed material, in 1971 and are approximates.

		Cost (p/m^2)
A)	Processes using paper only	
1.	Electro-sensitive Paper	135
2.	Heat-sensitive Paper (Thermofax)	95
3.	Photosensitive (UV recorder paper)	60
B)	Processes using paper and ink	
1.	Xerography or Laser printing	30
2.	Electrofax (R.C.A.)	40
3.	Magnetic (S.T.L)	35
4.	Electrostatic (Gould)	35

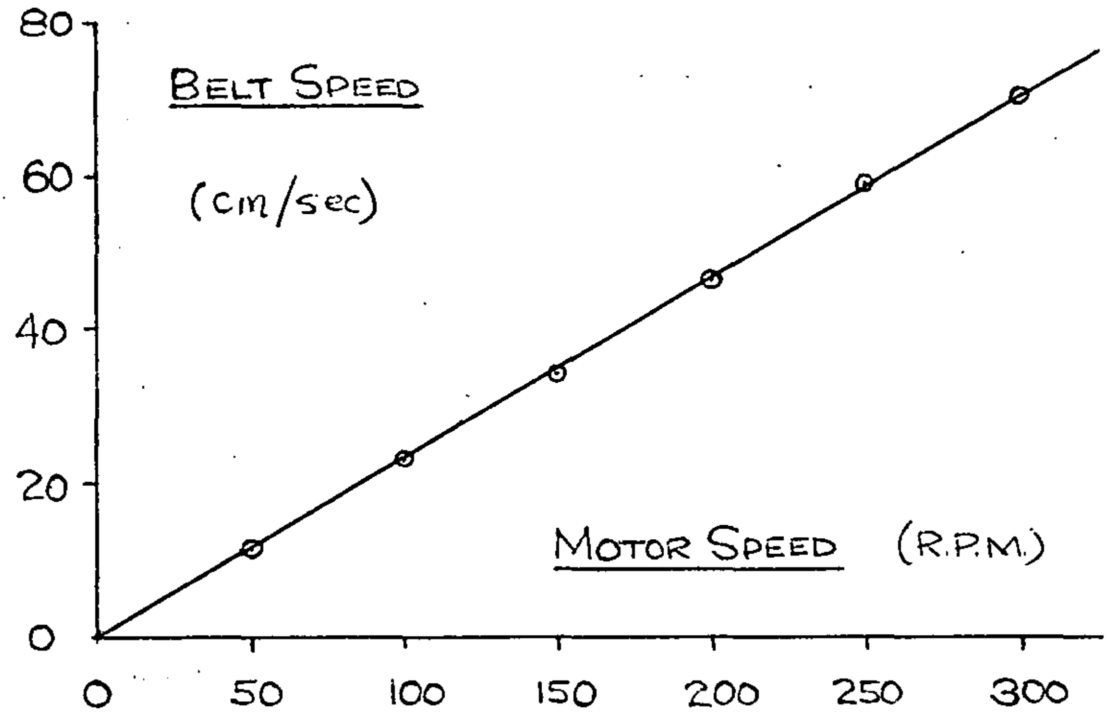


Fig A Belt Speed Calibration.

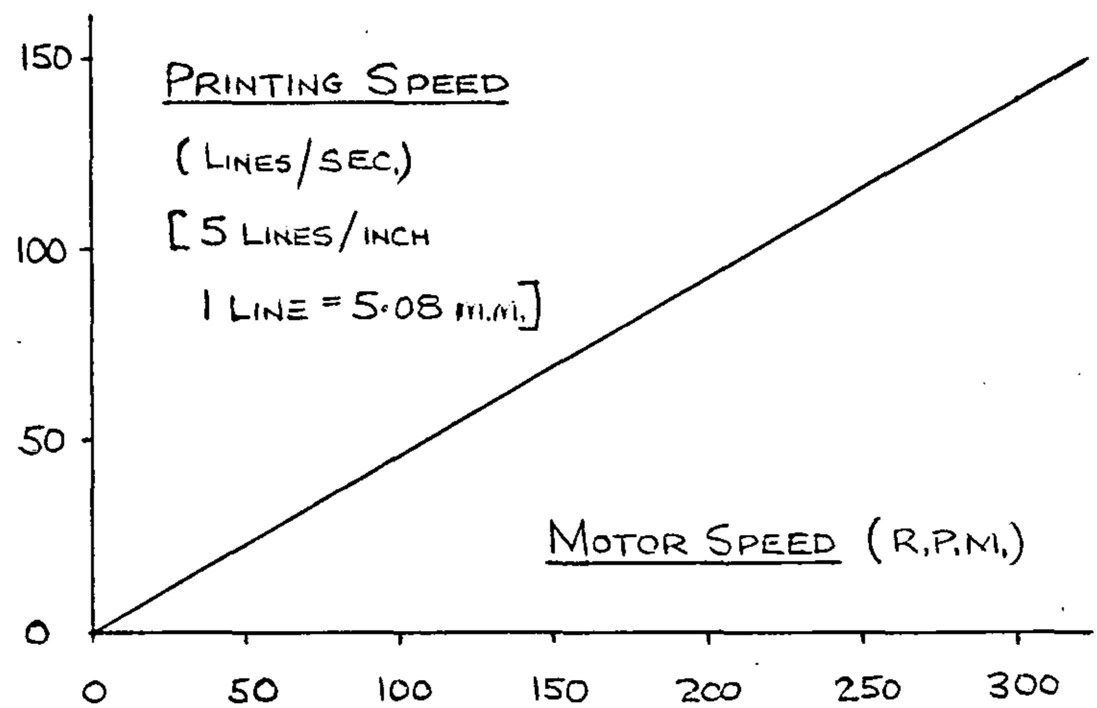


Fig. B Printing Speed v. Motor Speed

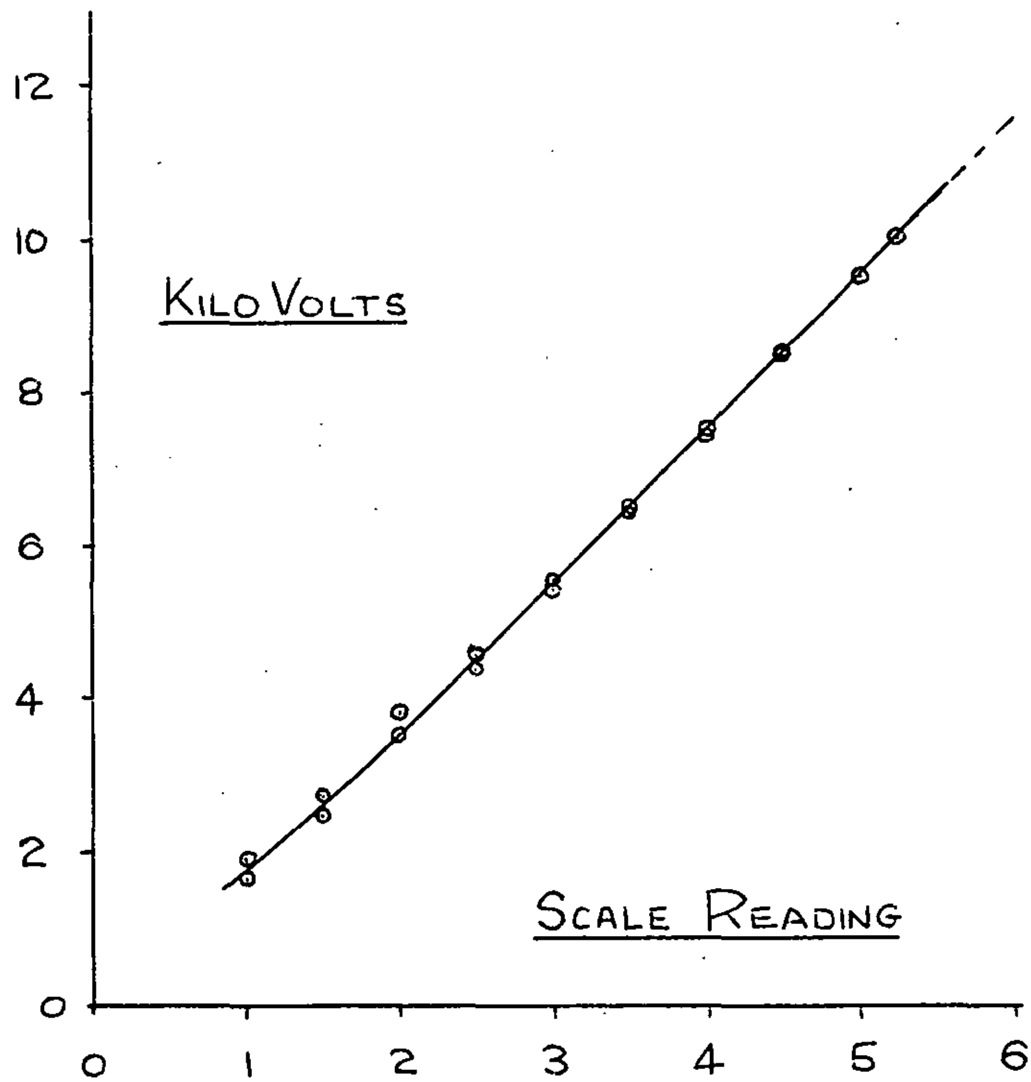


FIG. C

CALIBRATION CURVE FOR
ELECTROSTATIC VOLTMETER

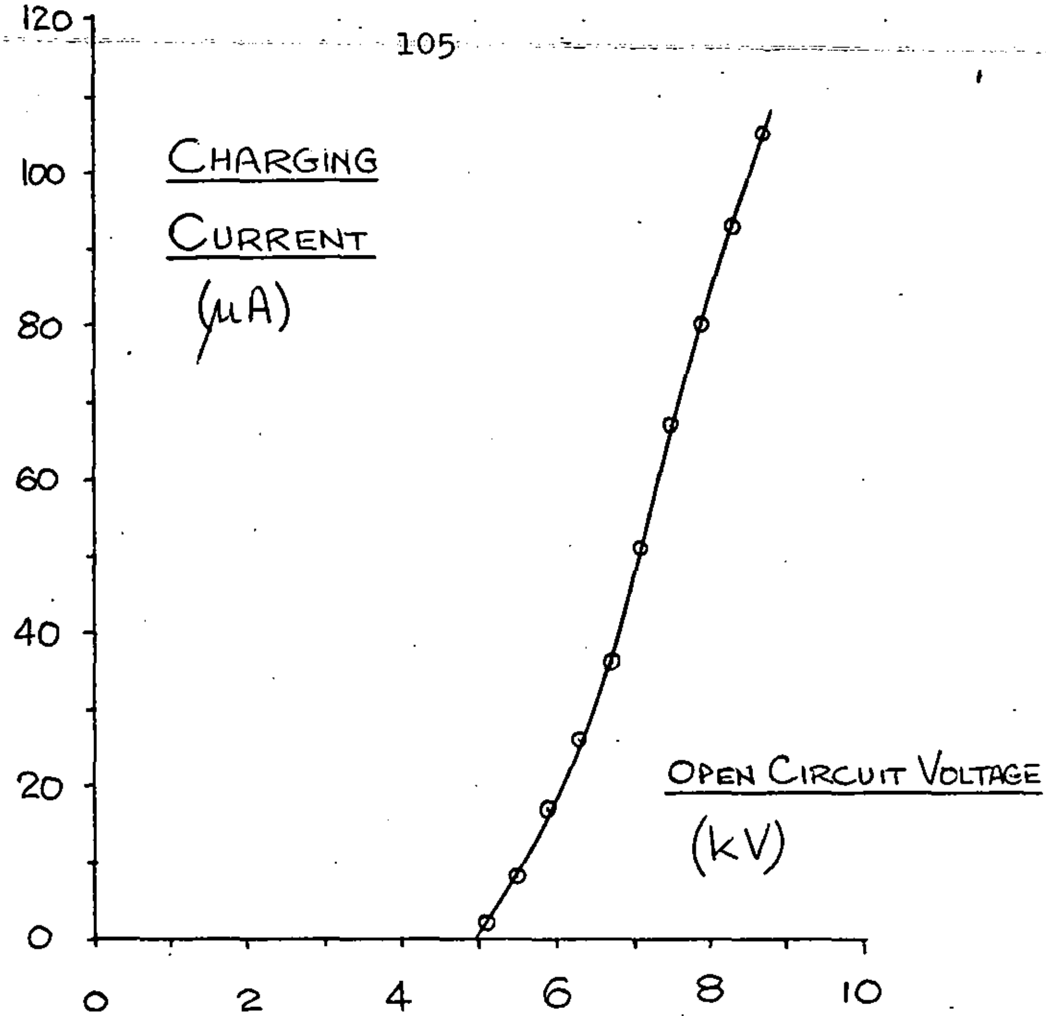


Fig D Dynamic Charging (Positive)

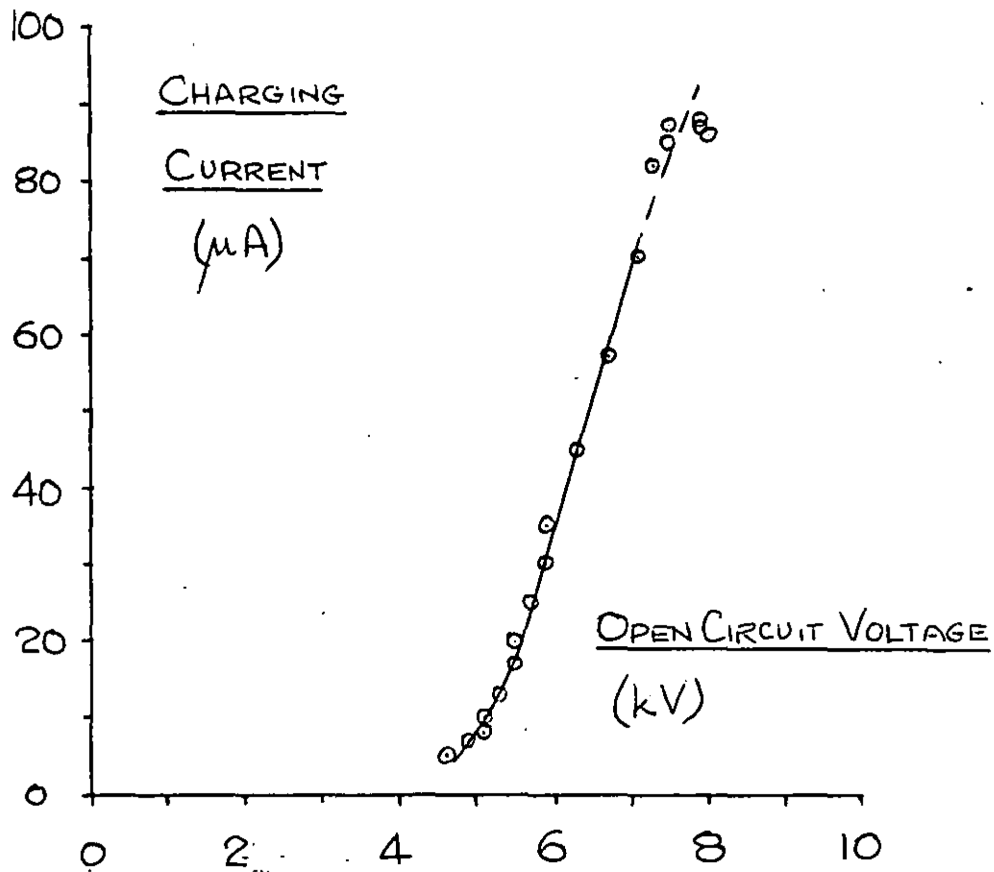


Fig E Dynamic Charging (Negative)

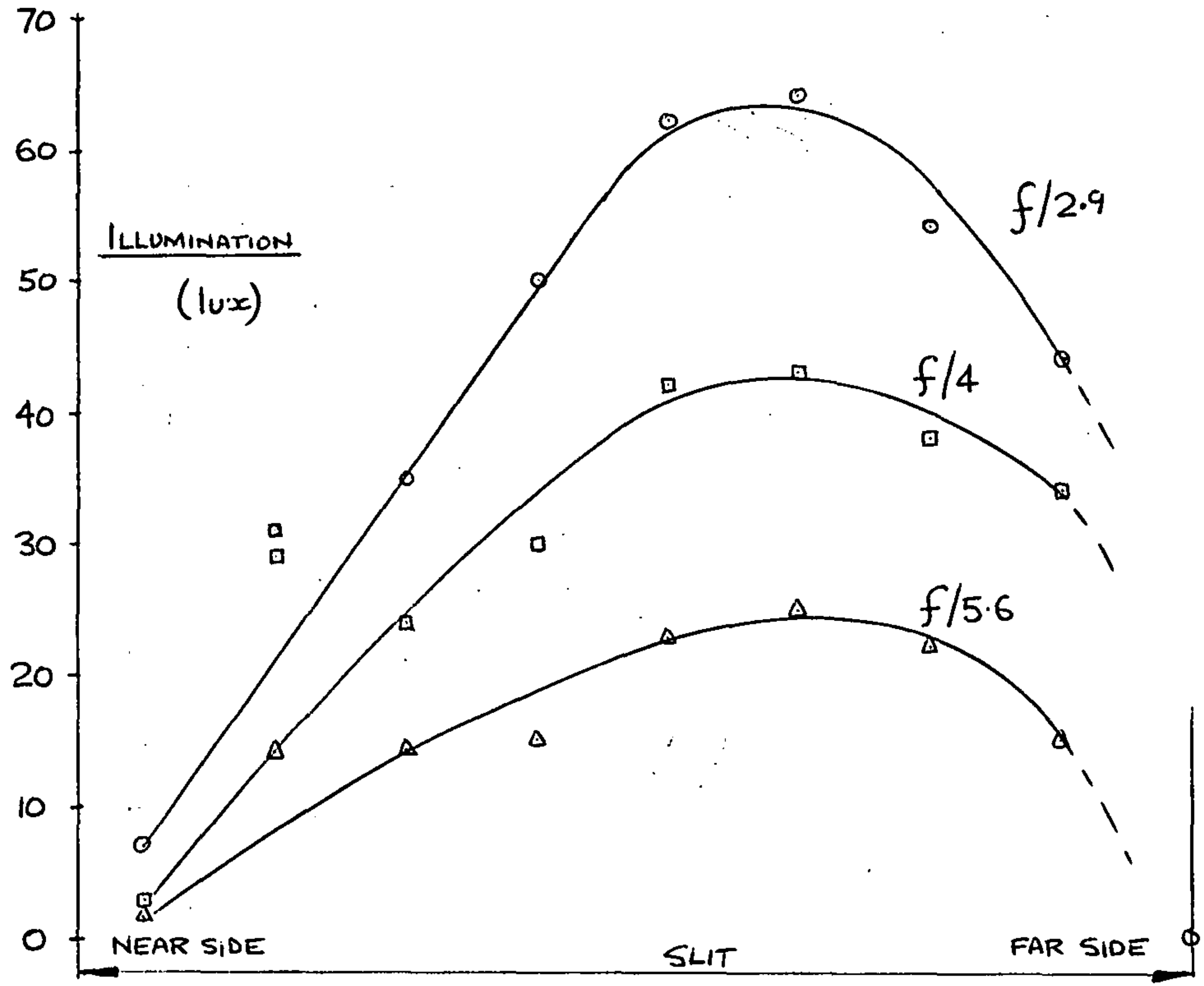


FIG F ILLUMINATION DISTRIBUTION

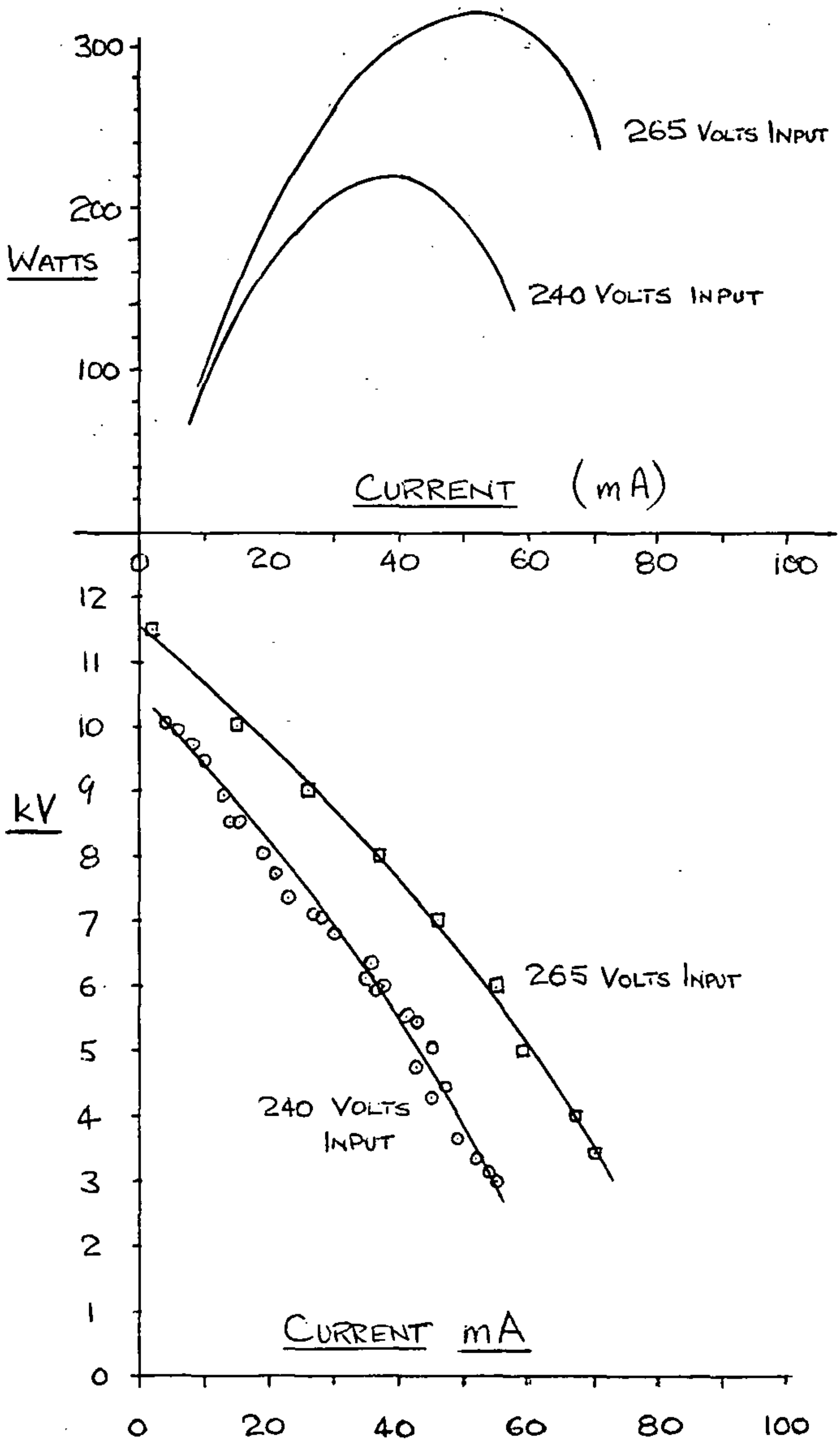


FIG G NEON SIGN TRANSFORMER OUTPUT

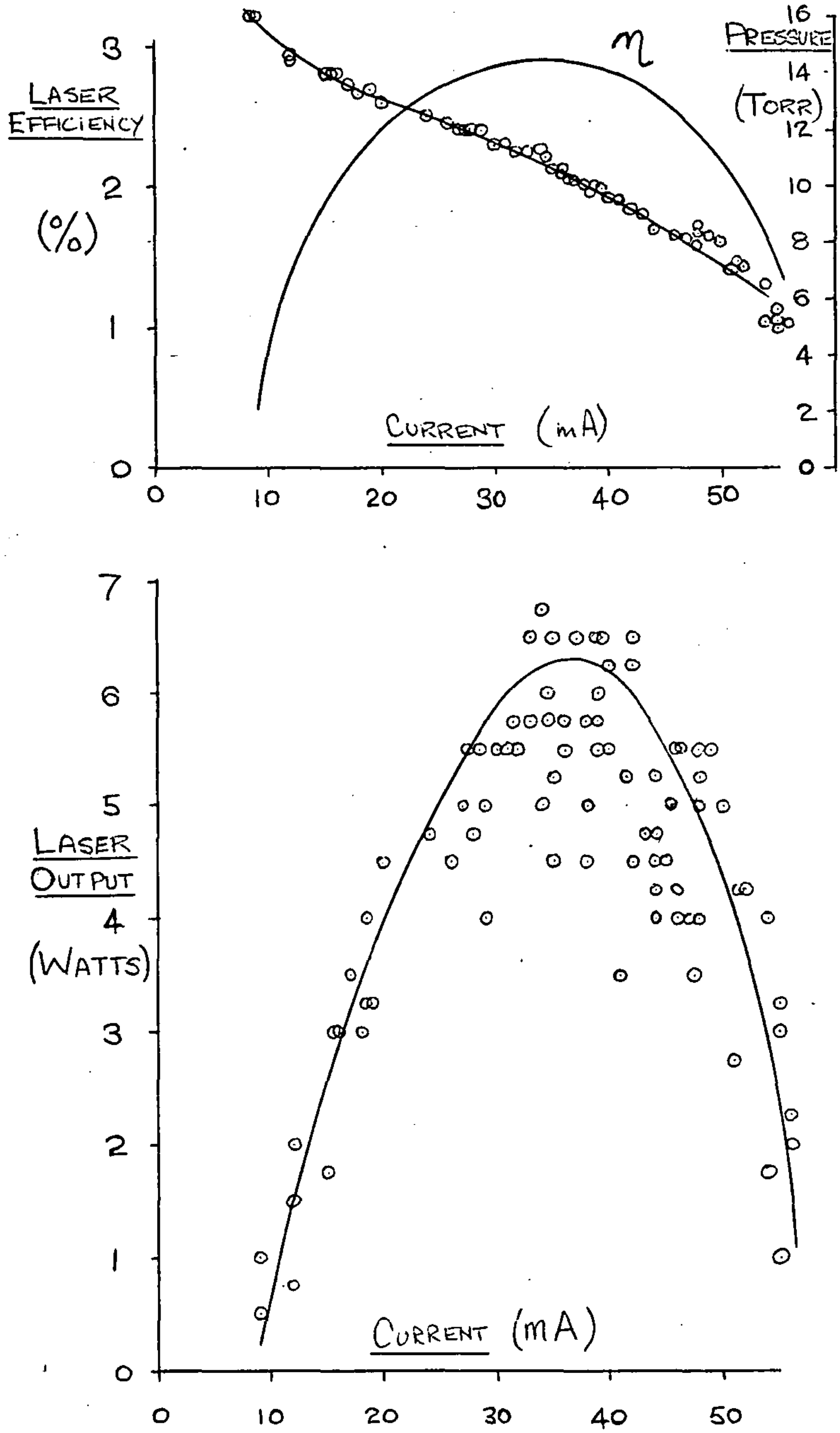
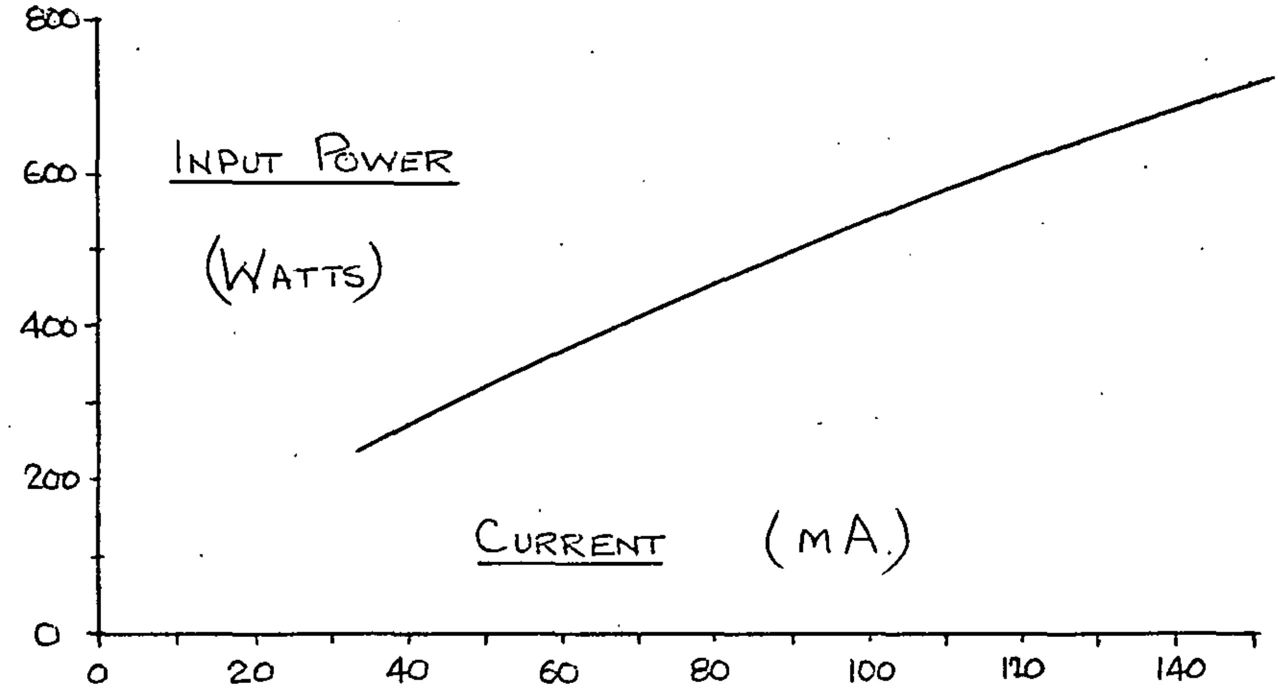


FIG H LASER OUTPUT (A.C.)(240V)



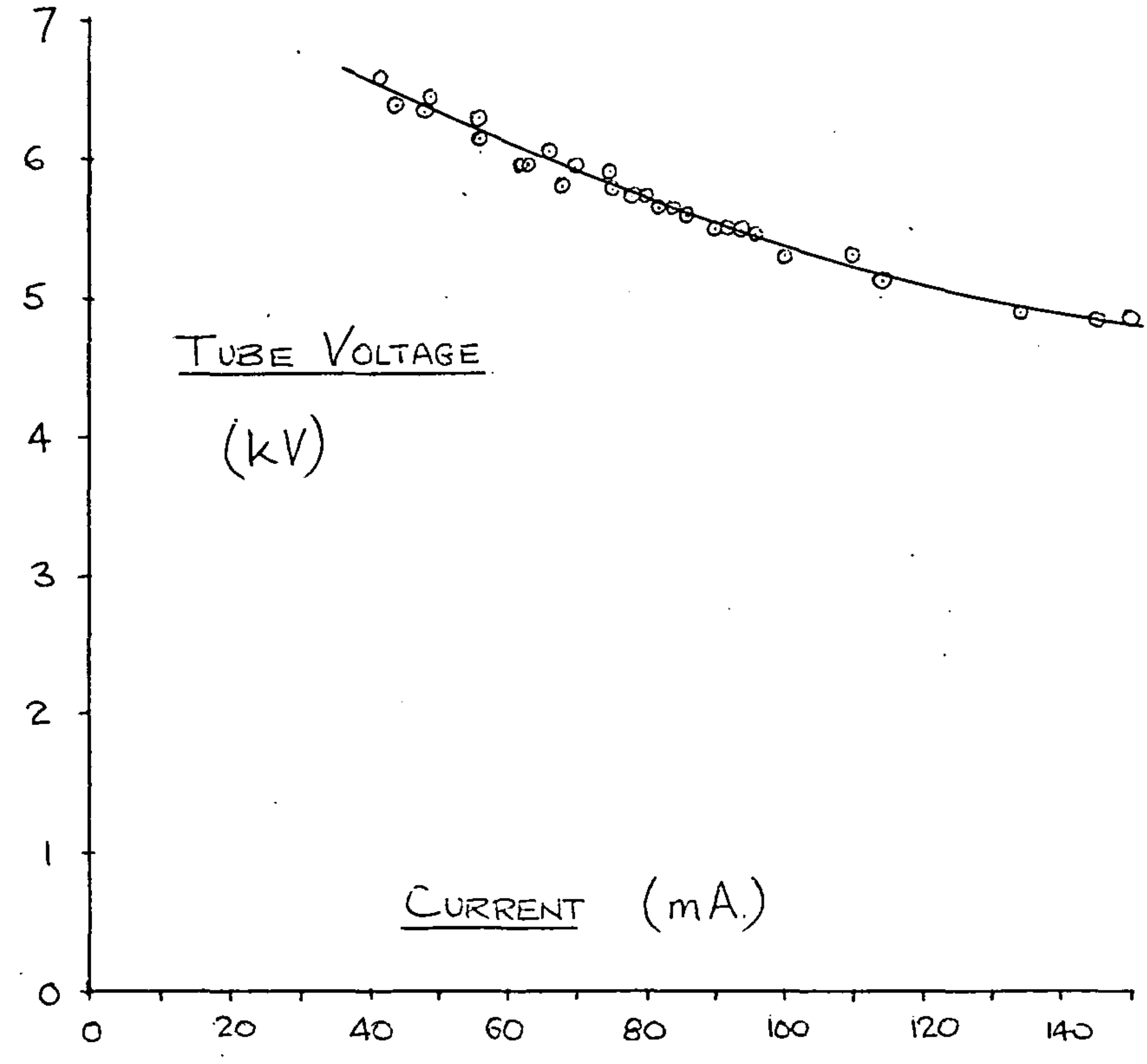
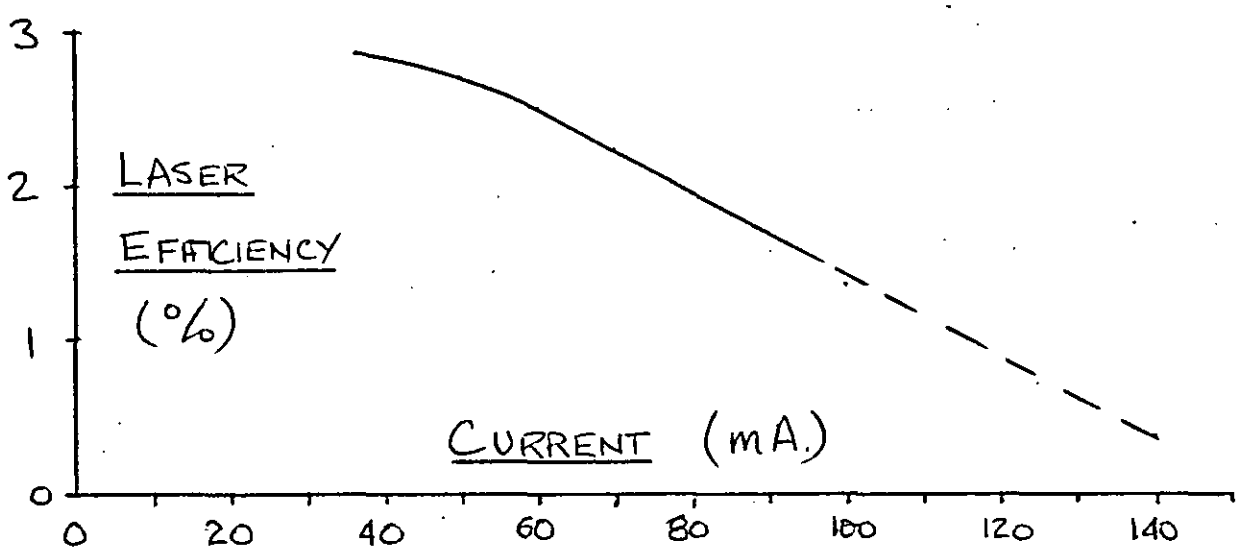


FIG I LASER INPUT (D.C.) AT 10 TORR.



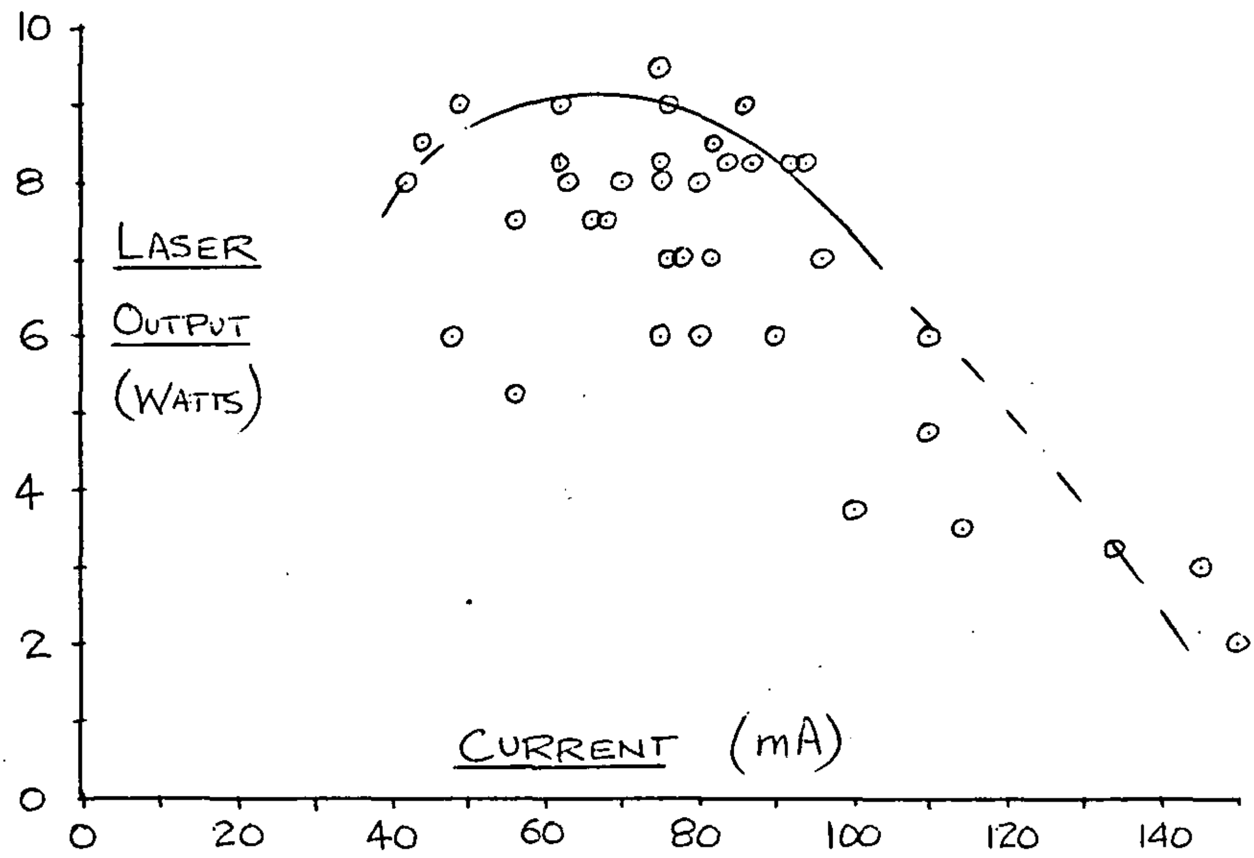


FIG J LASER OUTPUT (D.C.) (10 TORR)

				a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p
CHARACTER GENERATION	OPTICAL	ILLUM.	CHAR.				*												
			DOTS	*															
		C.R.T.	SCANNING								*	*							
			DOT MATRIX												*				
			CHAR. MATRIX			*							*					*	
	ELECTRO STATIC		WIRES						*		*								
			WIRED C.R.T.		*					*									
	MAGNET.		ARRAY													*			
	LASER		SCANNED																*
INTERMEDIATE MEDIUM (DRUM)					*	*									*	*		*	
PAPER			PLAIN		*	*									*	*		*	*
	TREATED		PHOTOGRAPH.	*			*					*							
			ELECTROFAX								*		*						
			PLASTIC						*	*									
			ELEC. SENS.											*					
DEVELOPMENT	DRY INK		CHEMICAL	*			*												
			CASCADE			*							*		*				
			BRUSH								*								
			BATH						*	*									
			AEROSOL															*	
	LIQUID		BATH														*		
FIXING			HEAT			*			*	*	*	*	*		*			*	*
			CHEMICAL	*															
			PRESSURE						*										
RUNNING			CONTIN.	*						*	*			*	*				
			INTERMIT.						*			*	*			*	*	*	*
ACCESS			IMMED.													*	*	*	*
			DELAYED	*		*		*	*	*	*		*	*	*				

(a)	Russian	1952	(2/14)	200 Ch./s
(b)	Battelle	1958	(3/25)	
(c)	Stromberg	c.1958	(3/21)	7000 Ch./s
(d)	Ferranti	1959	(3/9)	
(e)	Rank	1959	(3/22)	5000 Ch./s
(f)	Burroughs	1959	(3/29)	15000 Ch./s
(g)	A.B.Dick	1960	(3/26)	20000 Ch./s
(h)	R.C.A.	1961	(3/12)	10000 Ch./s
(i)	Anon.	1963	(3/10)	6000 Ch./s
(j)	S.C.3070	1963	(3/19)	500 Ch./s
(k)	Radiation	1964	(3/32)	63000 Ch./s
(l)	Xeronic	1964	(3/24)	5000 Ch./s
(m)	Ferrodot	1967	(3/35)	500 Ch./s
(n)	Gould	1970		6900 Ch./s
(o)	P.J.W. (A)	1963		(7200 Ch./s)
(p)	P.J.W. (B)	1965		(7200 Ch./s)

Fig. 3.2.1 Table of Non-Mechanical Printers.

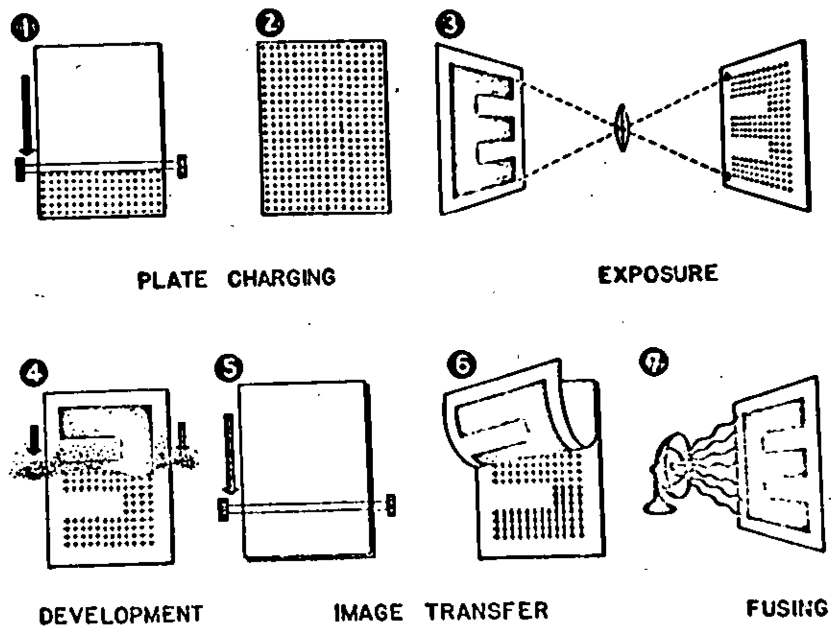


Fig. 5.1.1 Diagram of Stages in Xerography

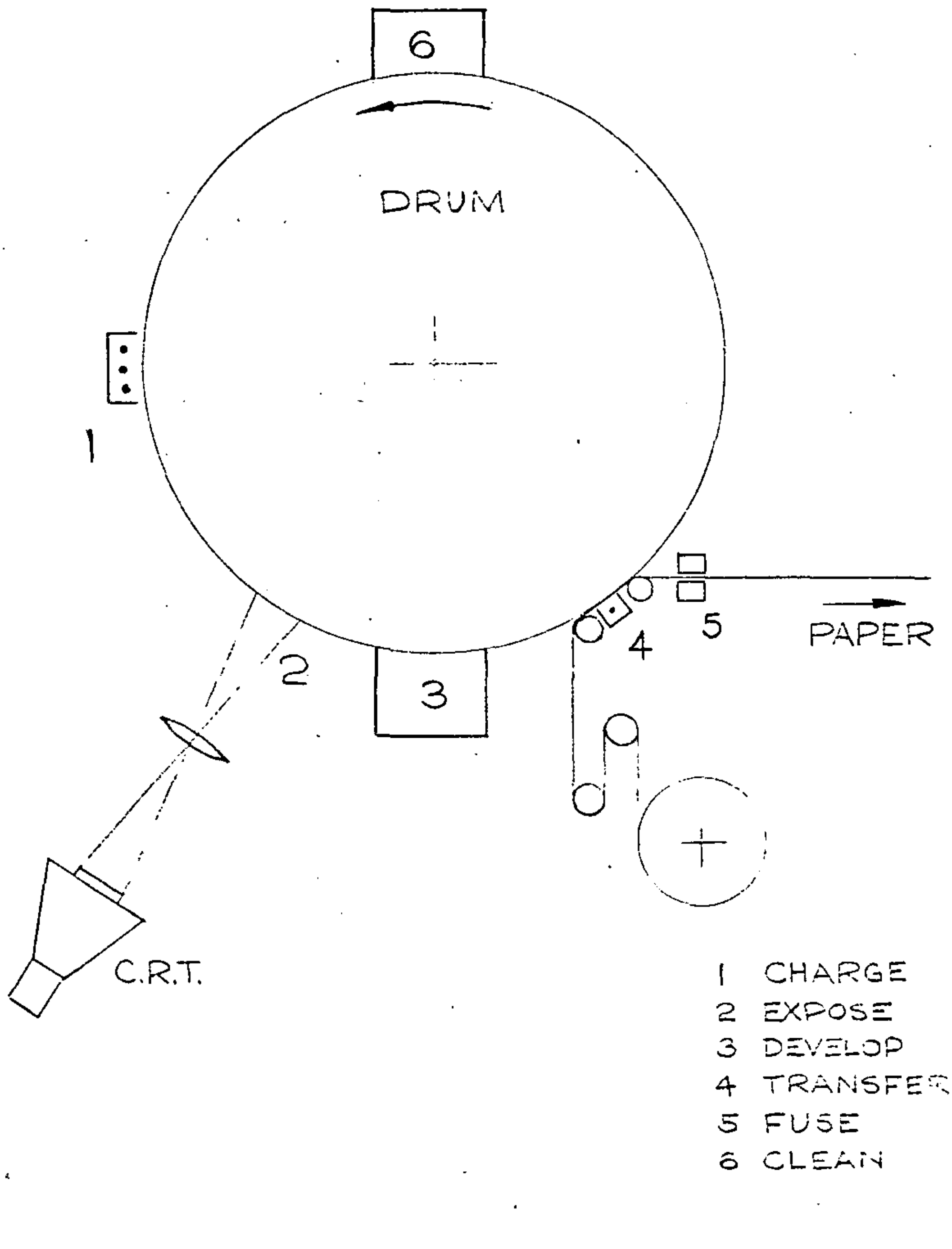


Fig. 5.1.2 Diagram of Proposed Printer

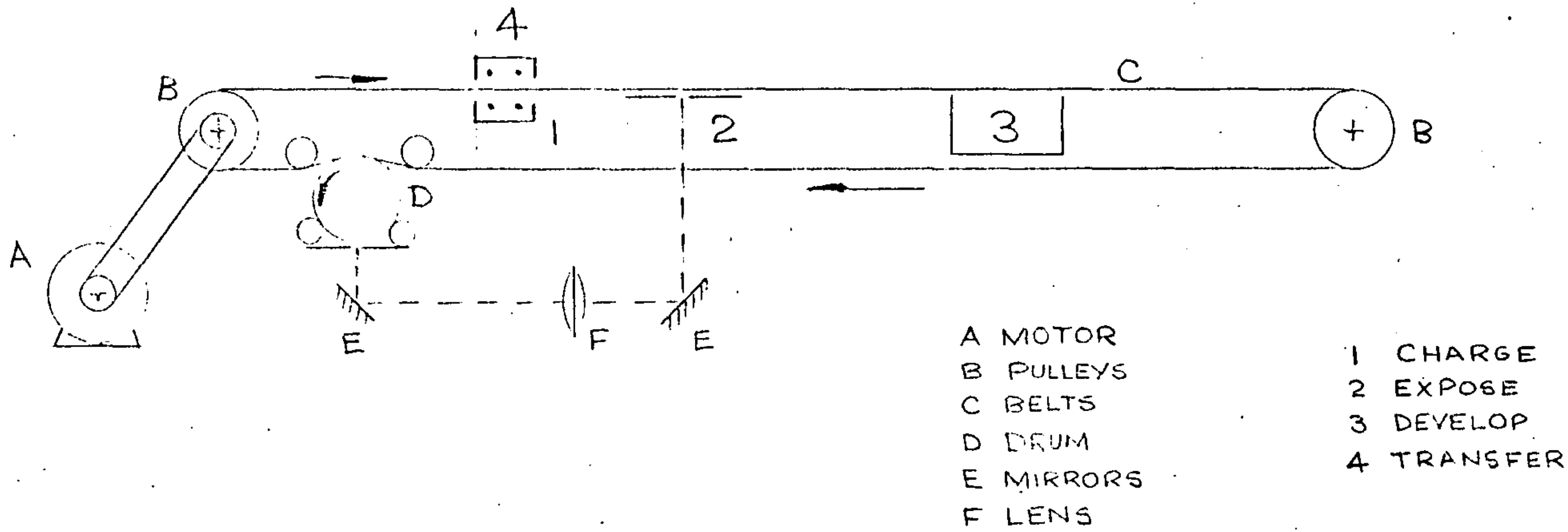


Fig. 5.2.1 Diagram of Xerographic TestRig

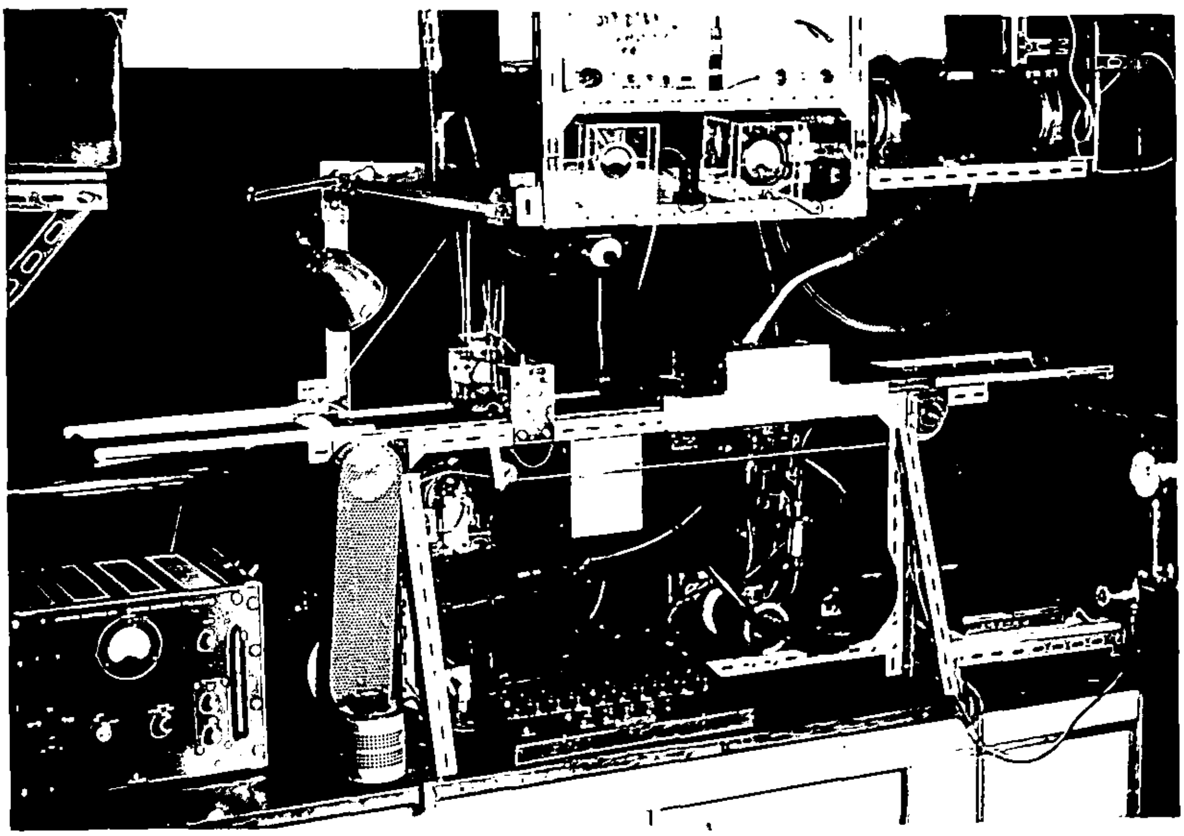


Fig. 5.2.2 Photograph of Test Rig.

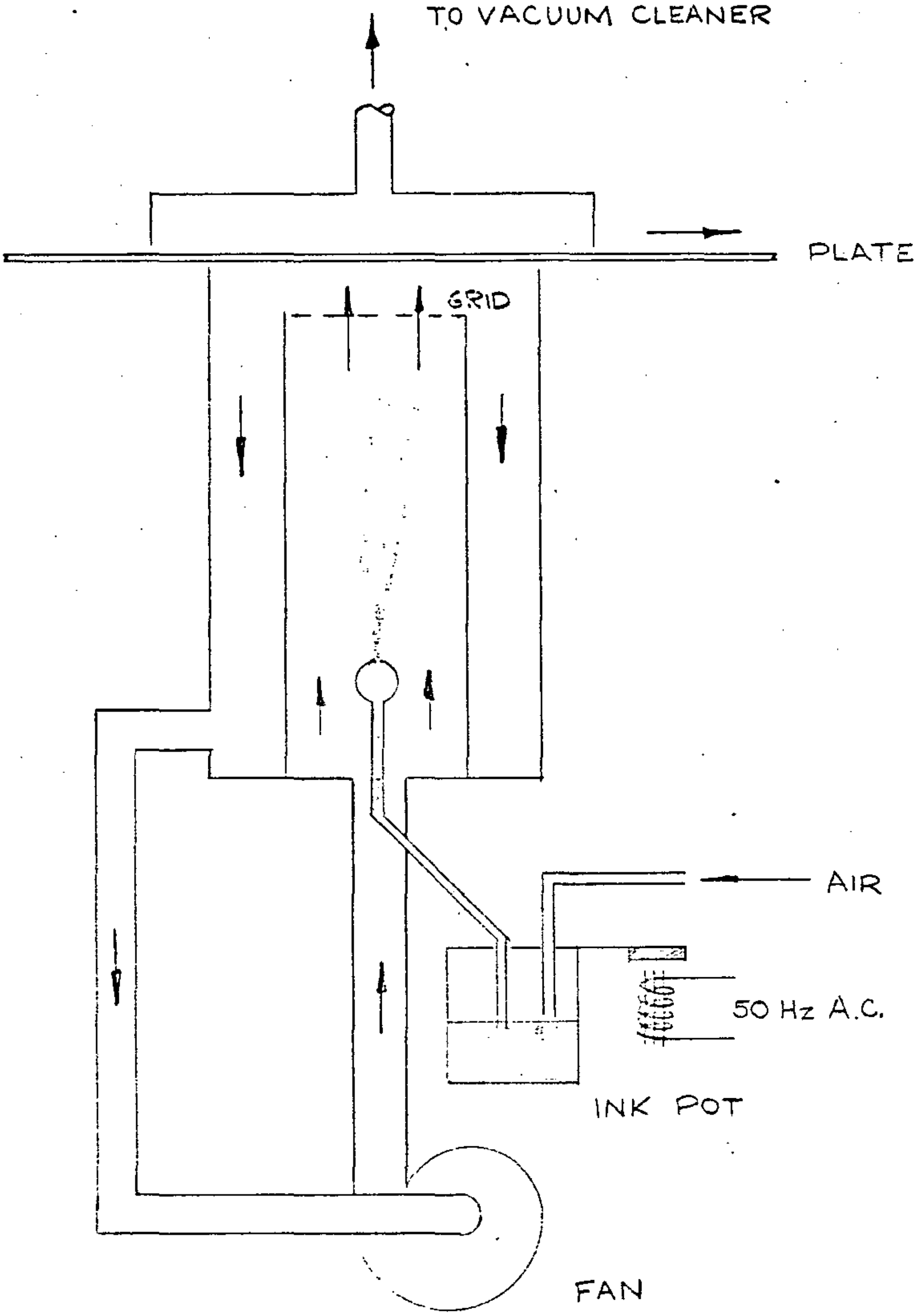
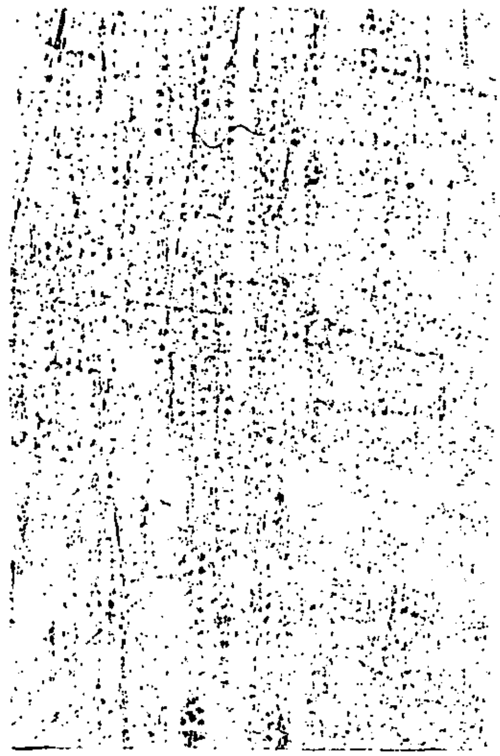


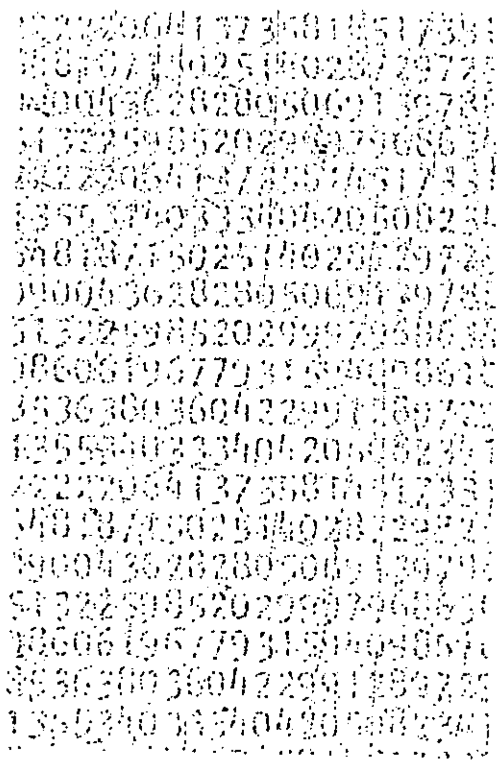
Fig. 5.2.3 Diagram of Inking System

Fig. 5.3.1 Typical Page (100 l.p.s.Hand Dev.)

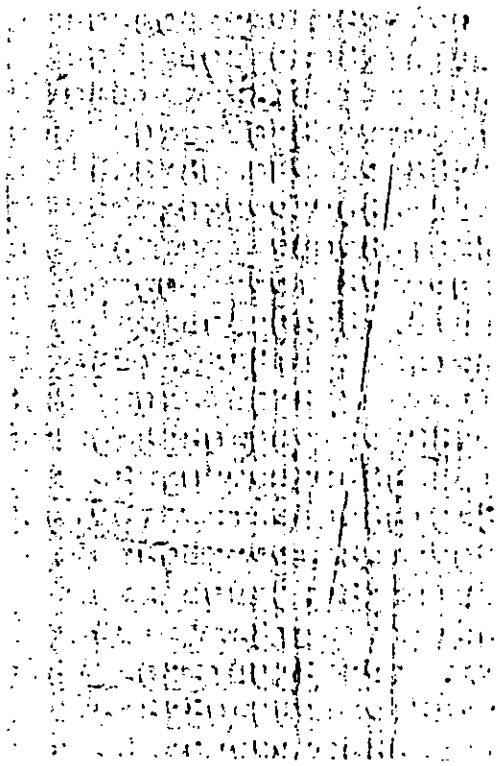
(a) 100μA (-ve.)



(b) 100μA (+ve.)



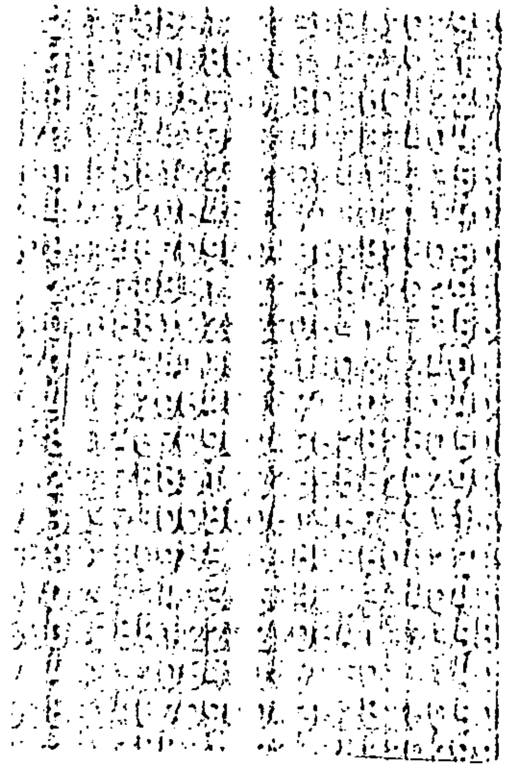
(c) 65μA(-ve.)



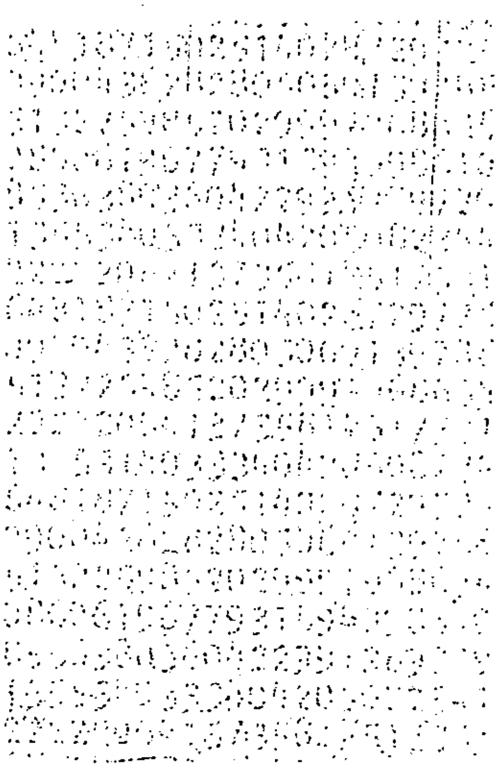
(d) 65μA (+ve.)

Fig. 5.3.2. Effect of Charging Current and Transfer Sign.

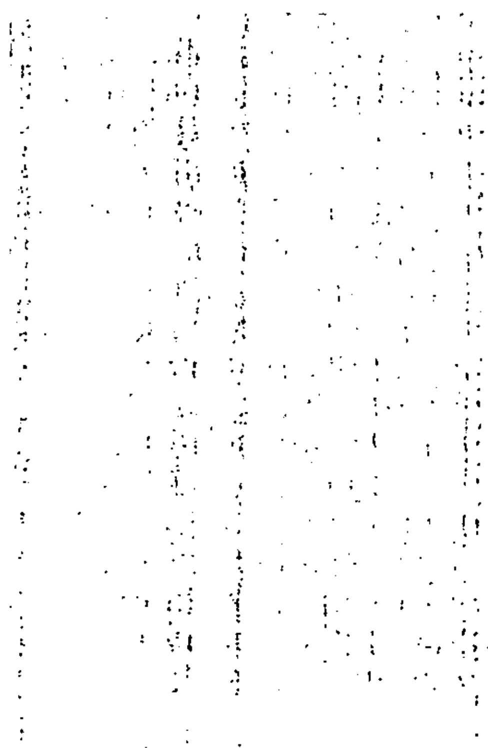
(e) 30μA (-ve.)



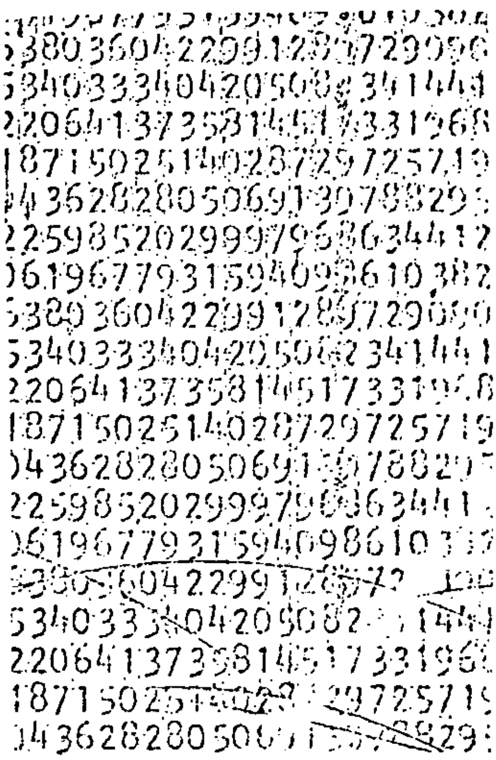
(f) 30μA (+ve.)



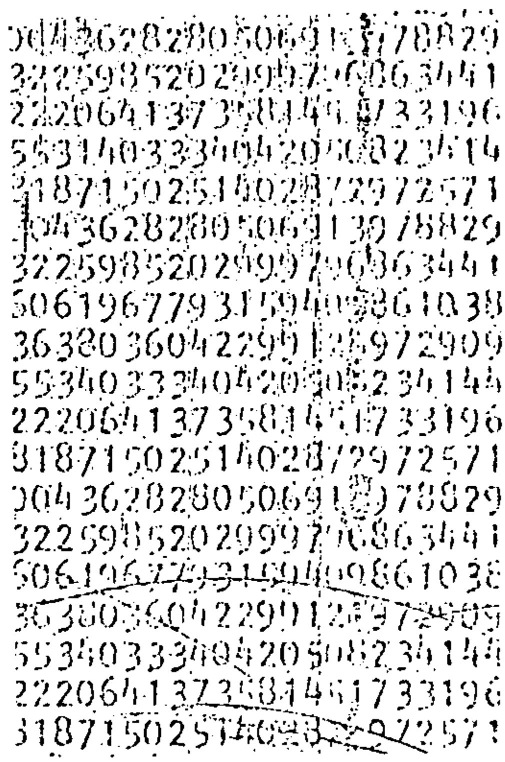
(g) 20μA (-ve.)



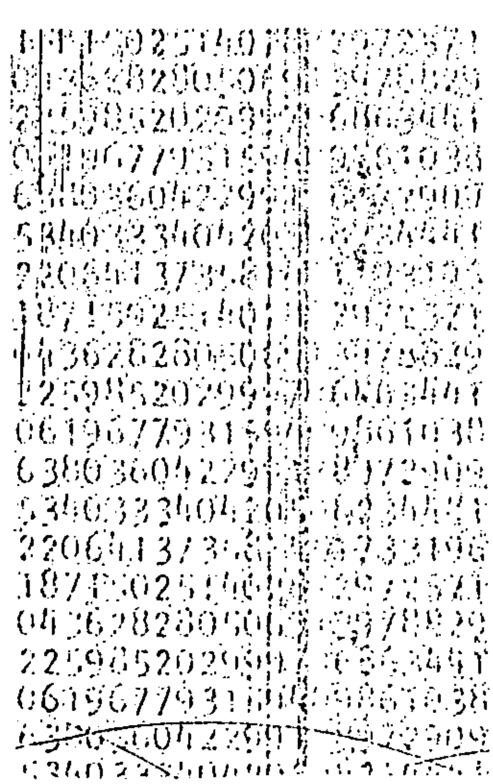
(h) 20μA (+ve.)



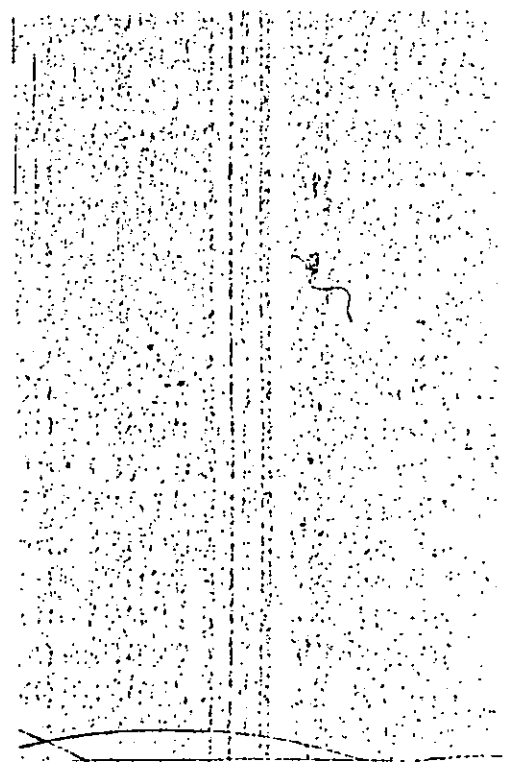
(a) 60lux



(b) 40lux

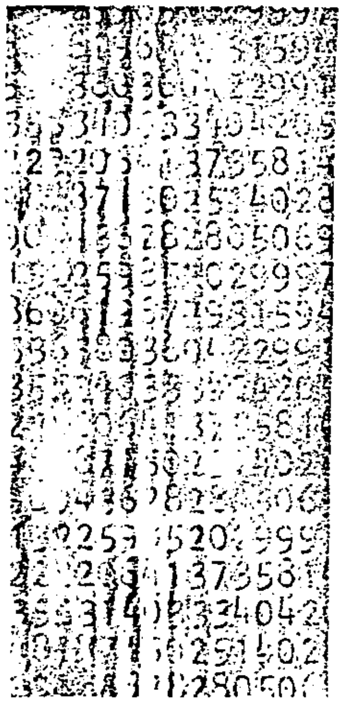


(c) 25lux

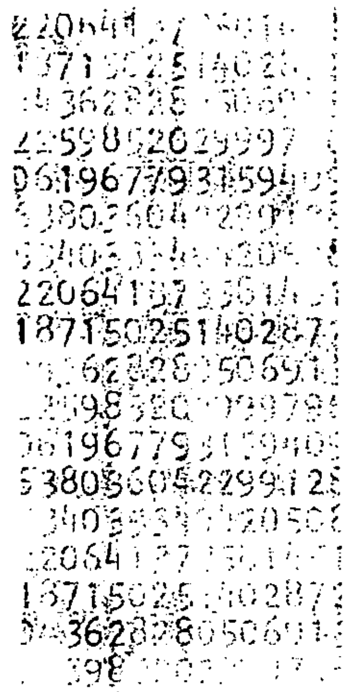


(d) 15lux

Fig. 5.3.3 Effect of Illumination (100l.p.s.)



(a) Over Inked



(b) Under Inked

Fig.5.3.4 Effect of Ink Quantity on High Speed Aerosol Development (100l.p.s.)

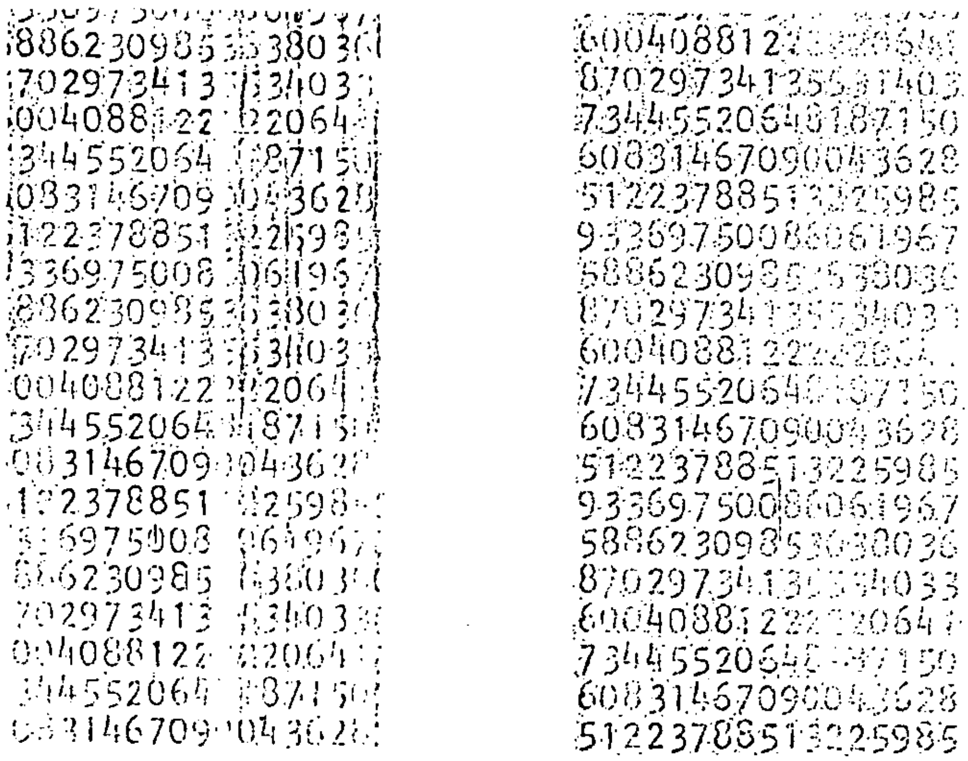


Fig. 5.3.5 Typical Examples of 100 Line per Second Printing with Aerosol Development

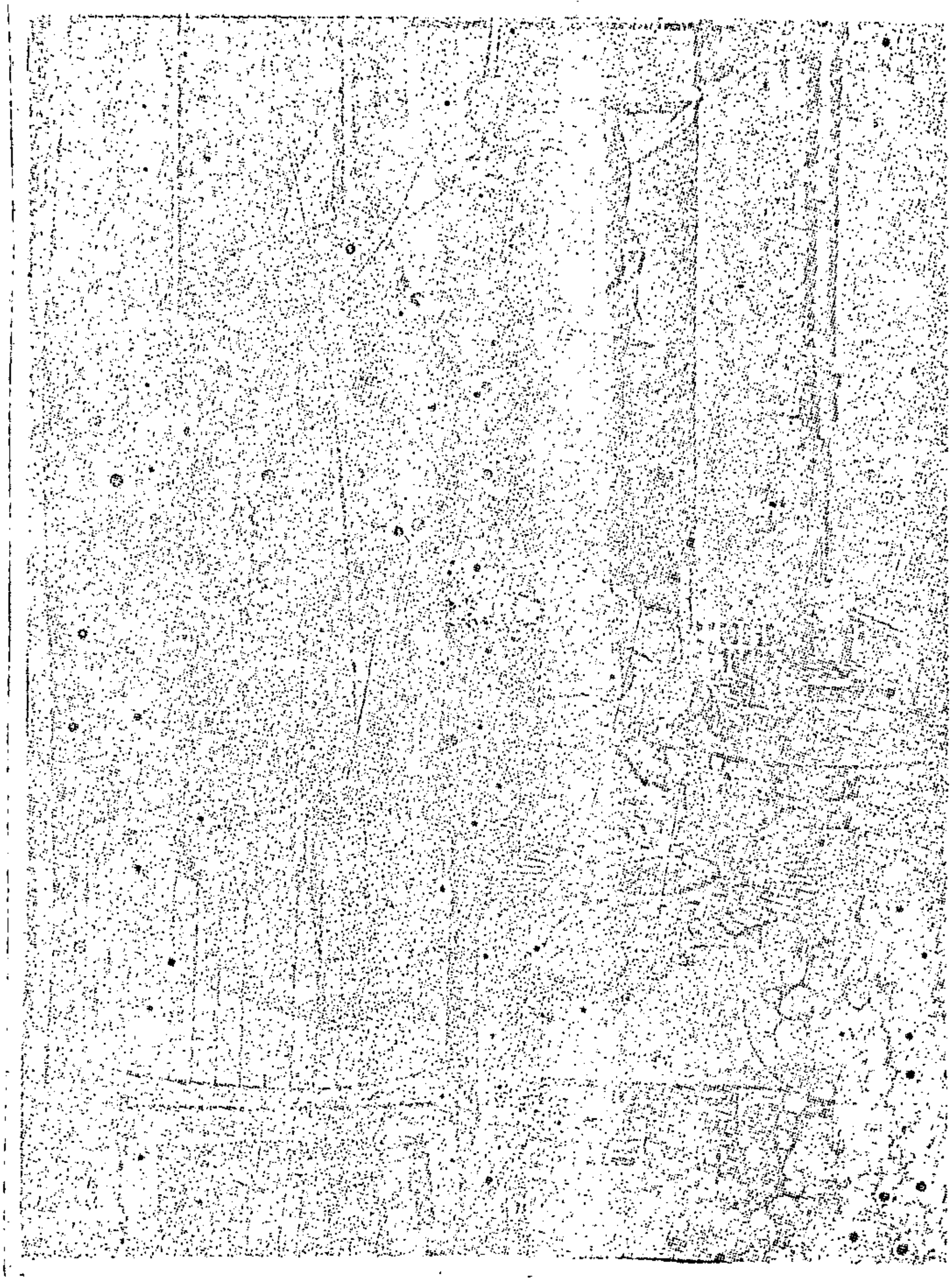


Fig. 5.3.6 Half Tone Printing Sample

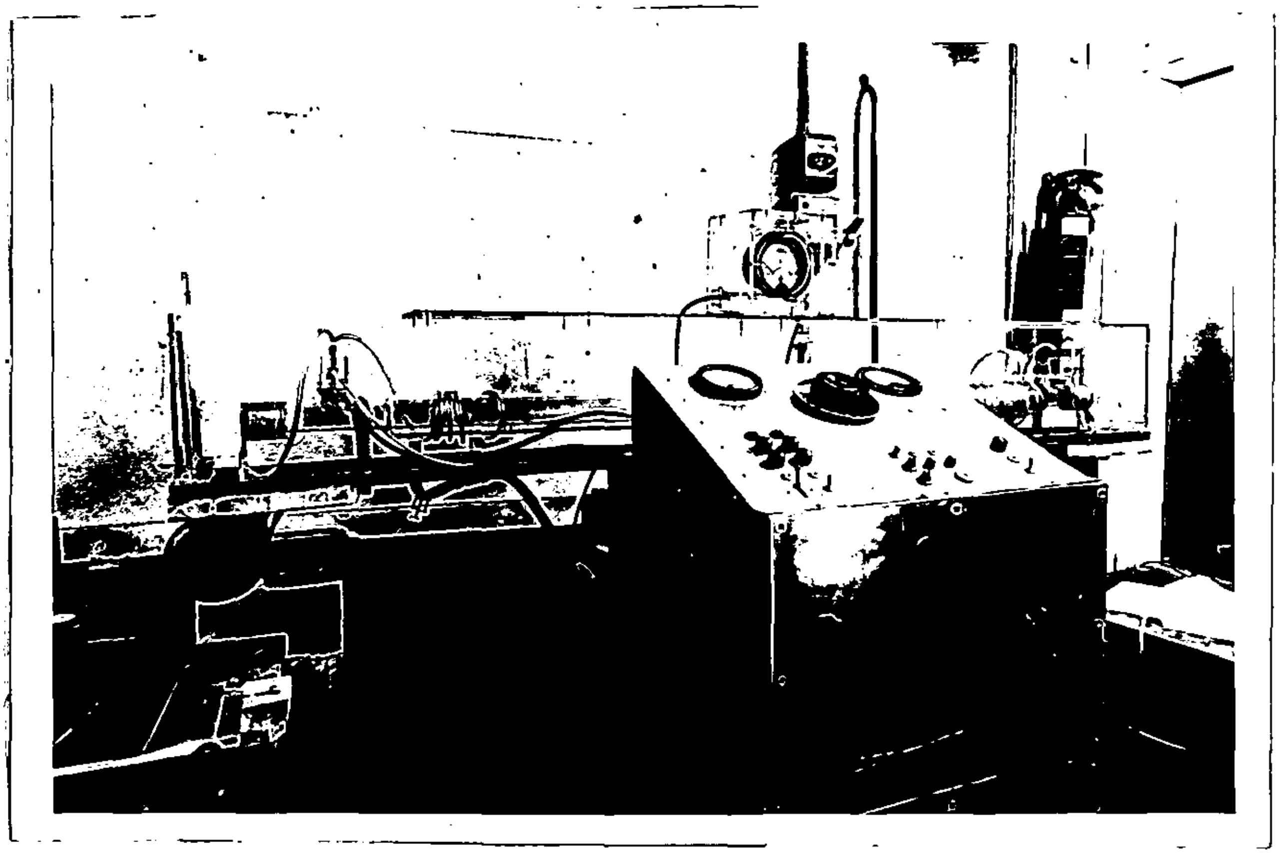


Fig. 7.2.1 Photograph of Laser

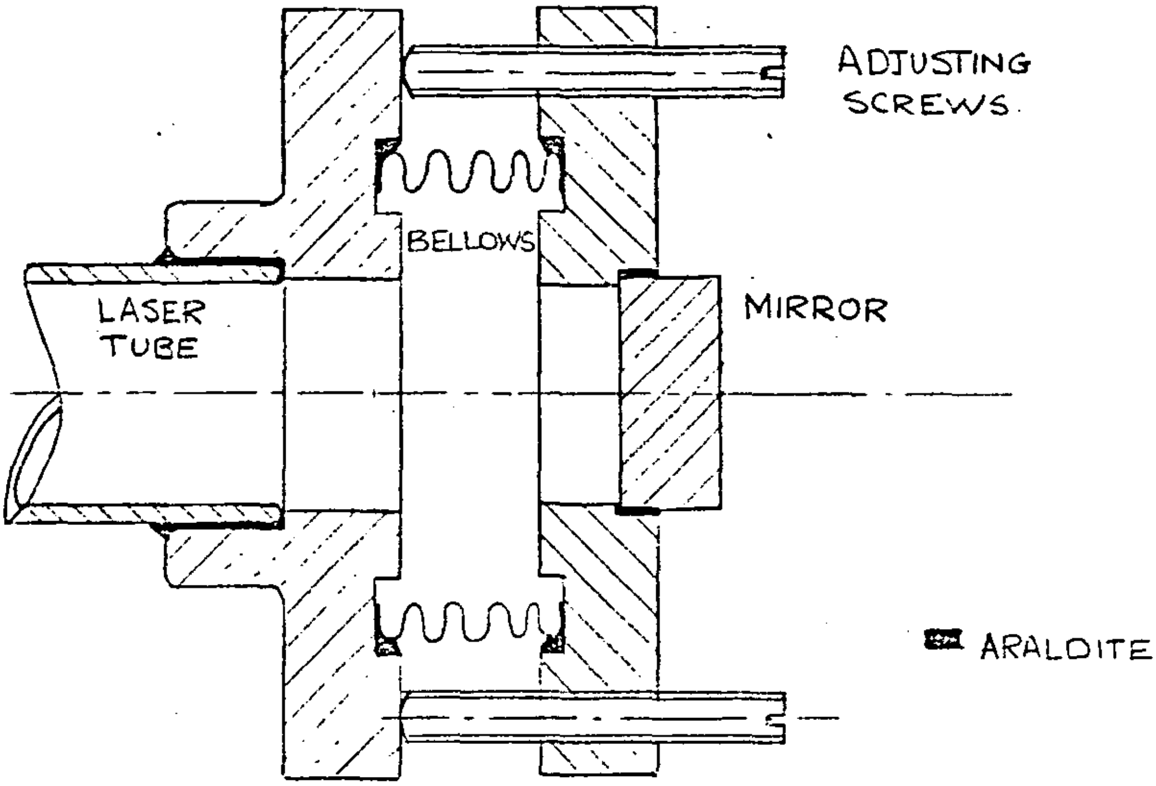


Fig. 7.2.2(a) Diagram of Original Mirror Mount

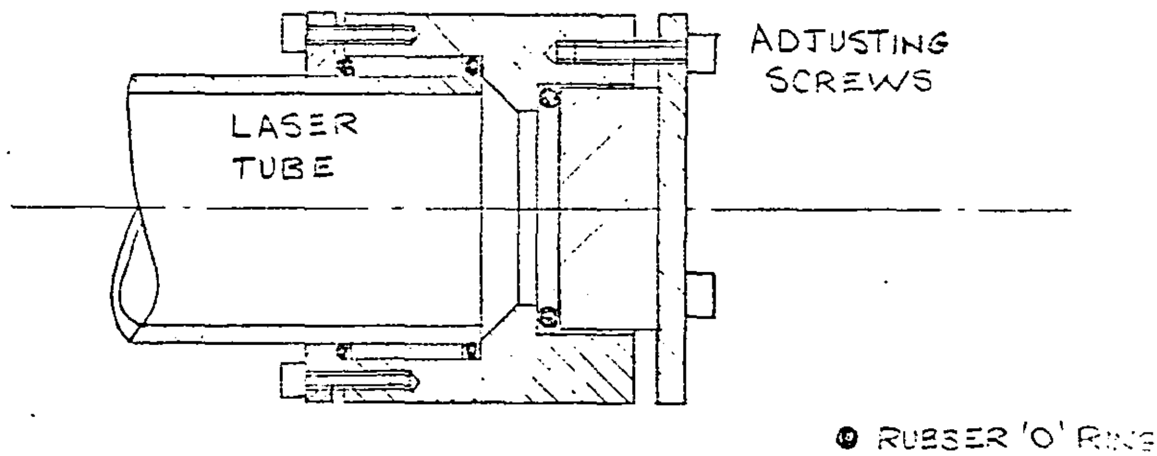


Fig. 7.2.2(b) Diagram of New Mirror Mount

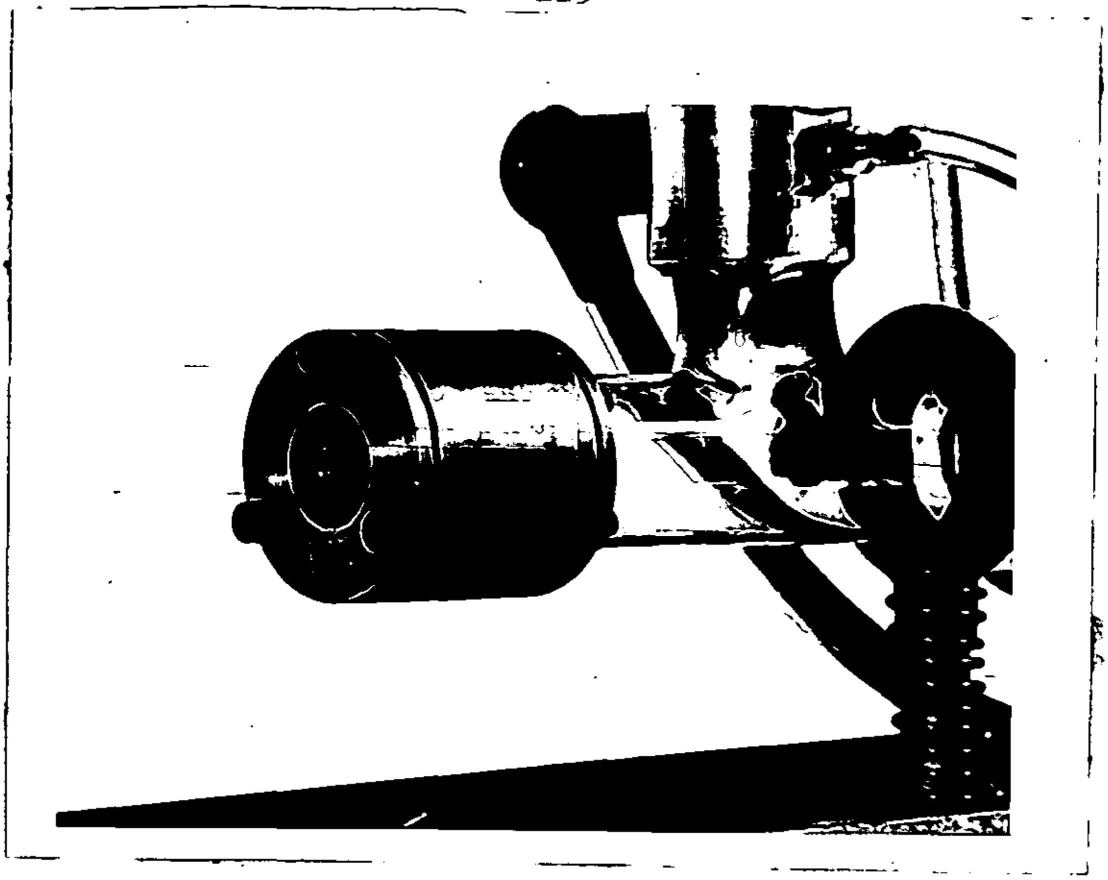


Fig. 7.2.3 Photograph of Mirror Mount

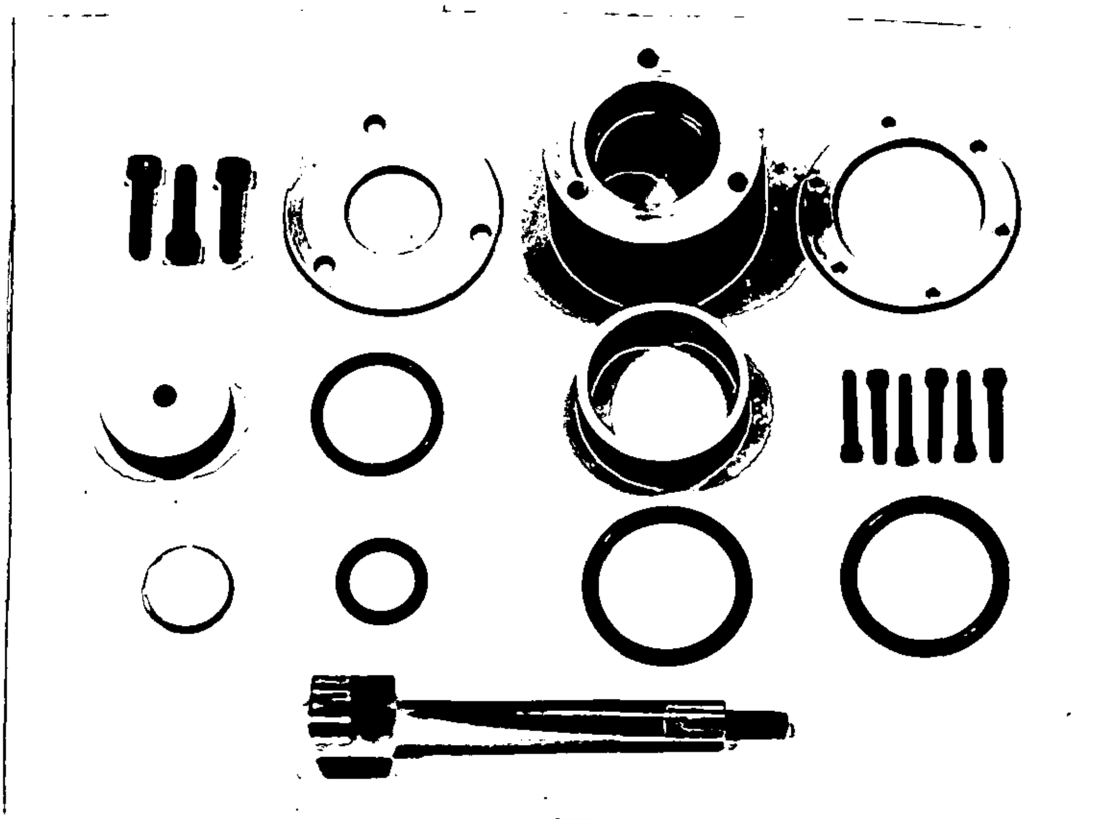


Fig. 7.2.4 Photograph of Mirror Mount Components

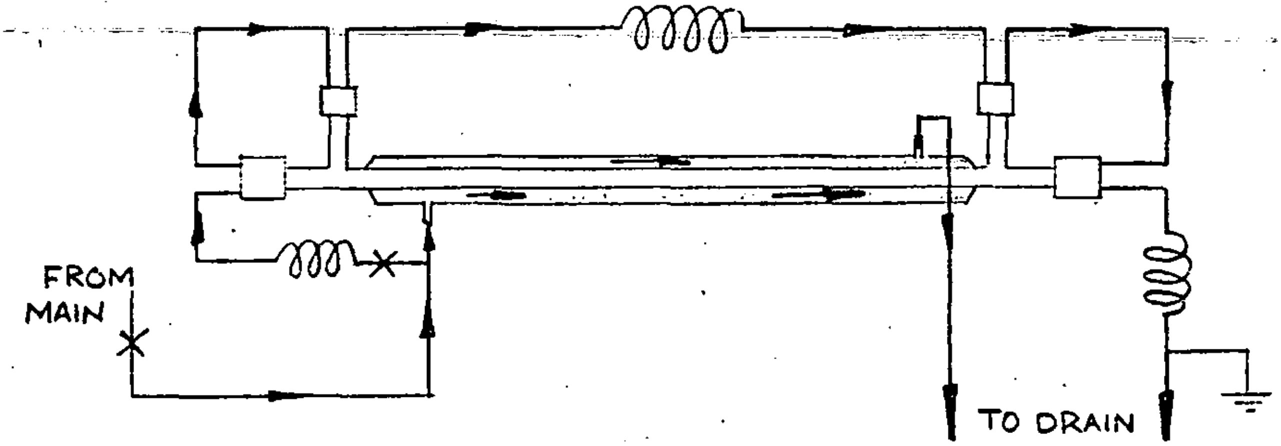


Fig.7.2.5(a) Diagram of Laser Water System

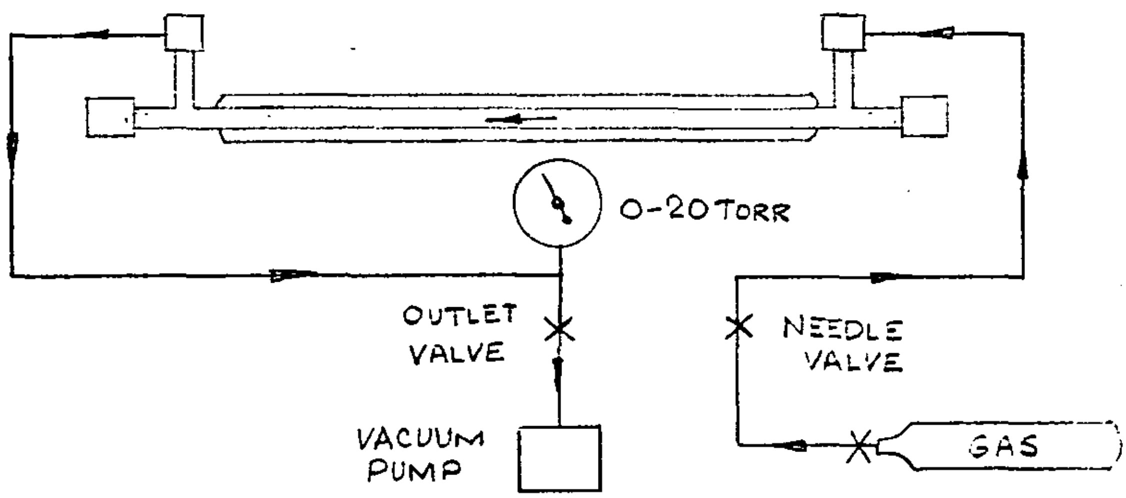


Fig. 7.2.5(b) Diagram of Laser Gas System

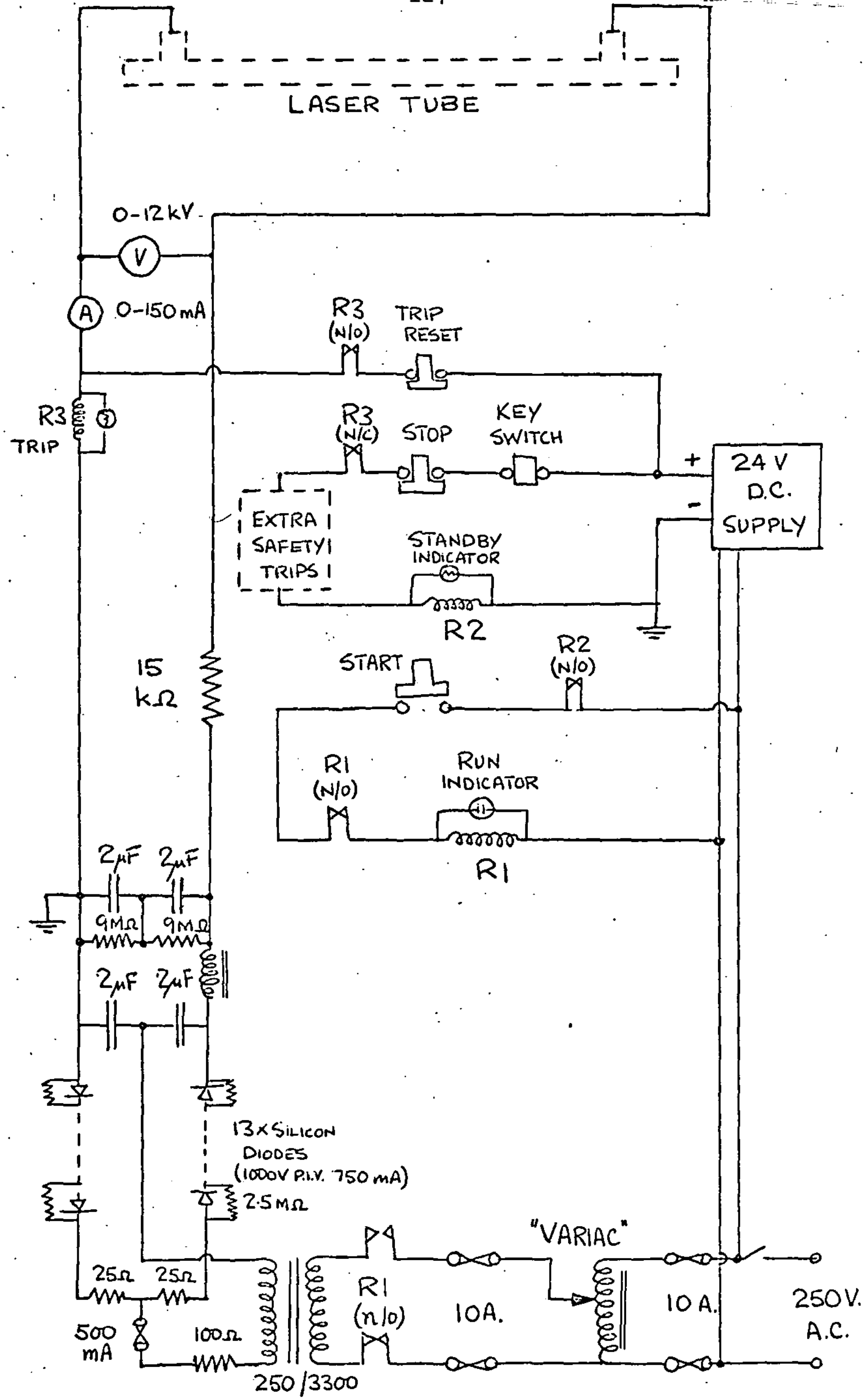


FIG. 7.2.6 LASER D.C. POWER SUPPLY

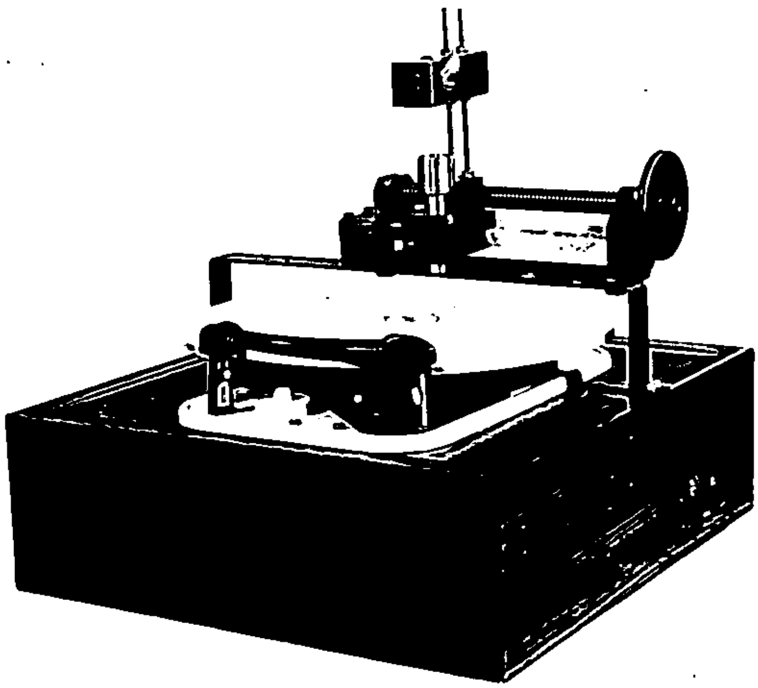


Fig. 7.3.1 Photograph of Turntable Apparatus

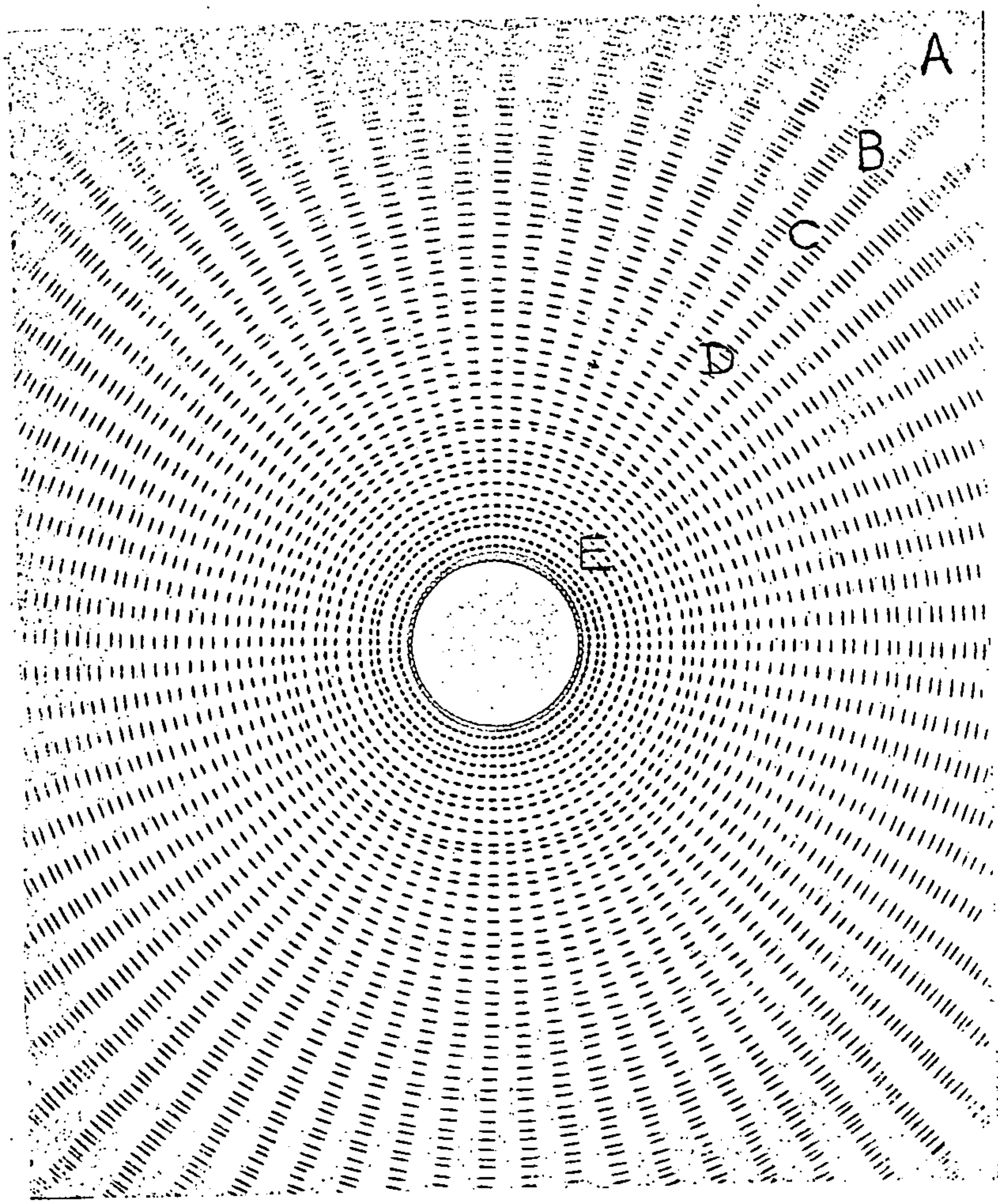
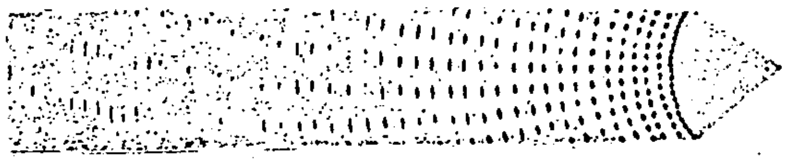
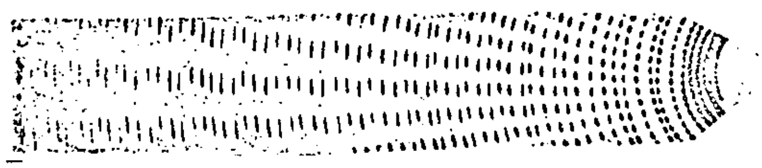


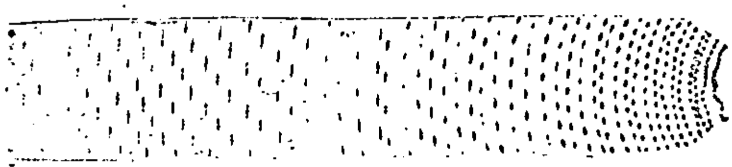
Fig. 7.3.2 Typical Test Sheet.



(a) Over Inked.



(b) Normally Inked.



(c) Under Inked.

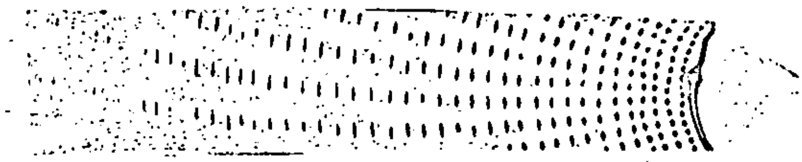
Fig. 7.3.3 Examples of Inking.

(a) Gloss Paper.

(b) Writing Paper.

(c) Blotting Paper.

Fig. 7.3.4 Examples of Paper Types.



(a) Normally Charged.

(b) Under Charged.

Fig. 7.3.5 Examples showing effect of Charging.

Fig. 7.3.6 Portion of Chopped Test Sheet.

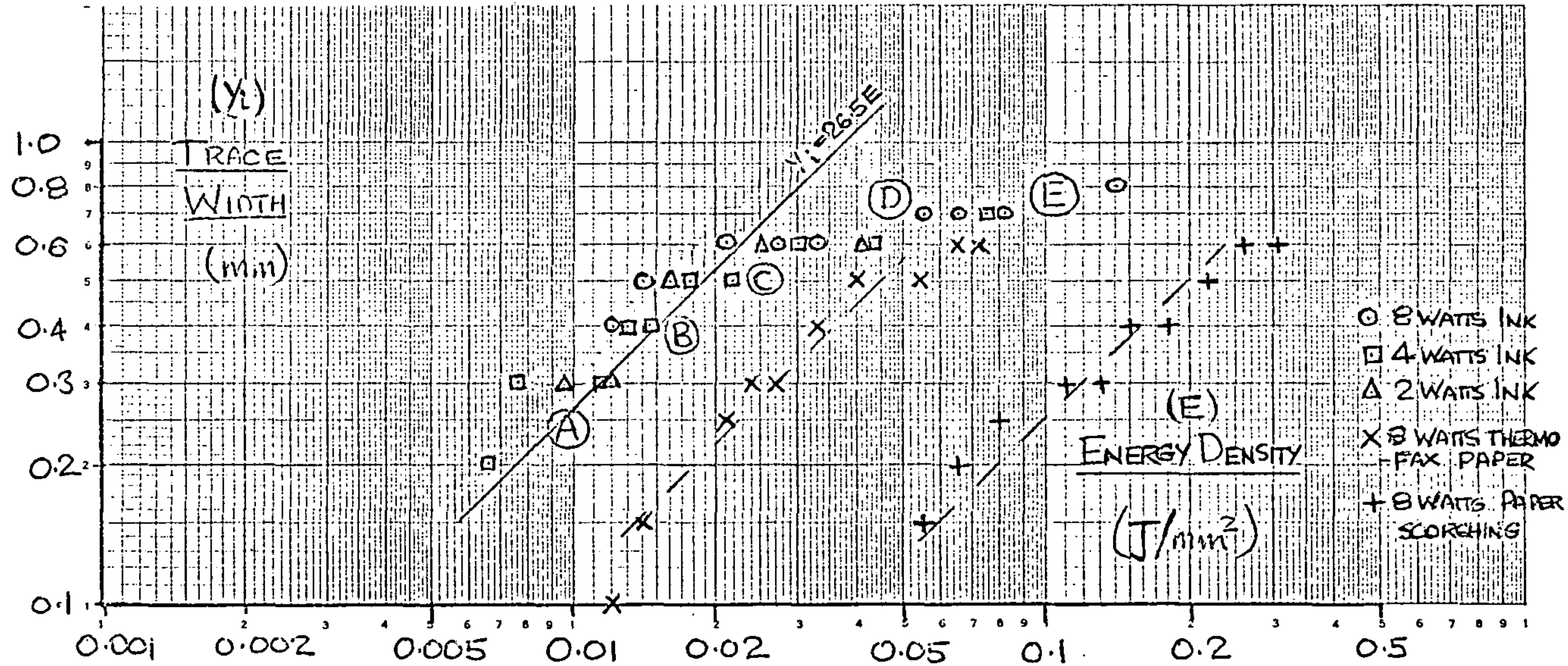


FIG. 7.3.7 LASER PRINTING (A.C.) WITH DIFFERENT MEDIA.

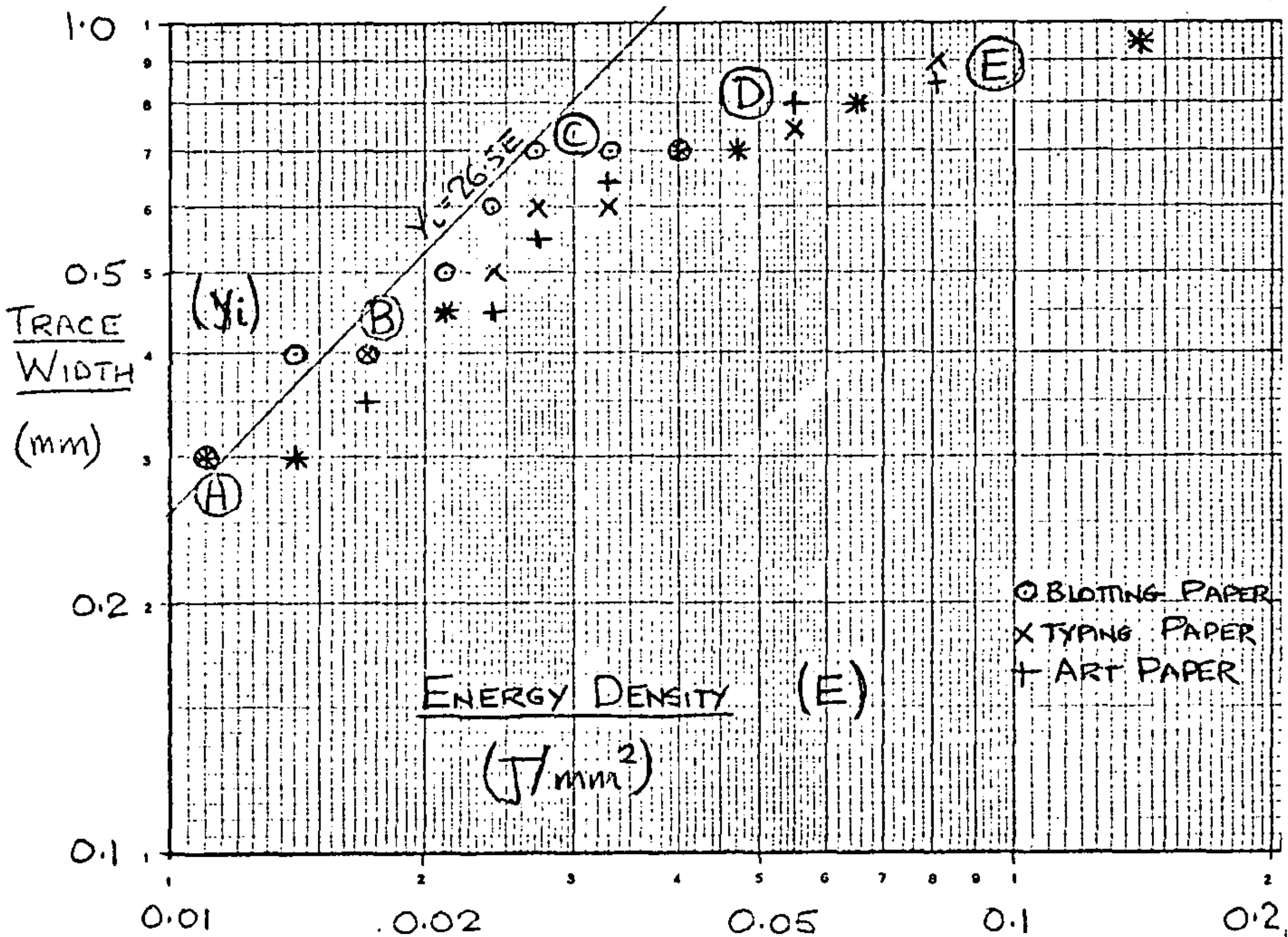


FIG 7.38. LASER PRINTING (D.C.) INK ON PAPER

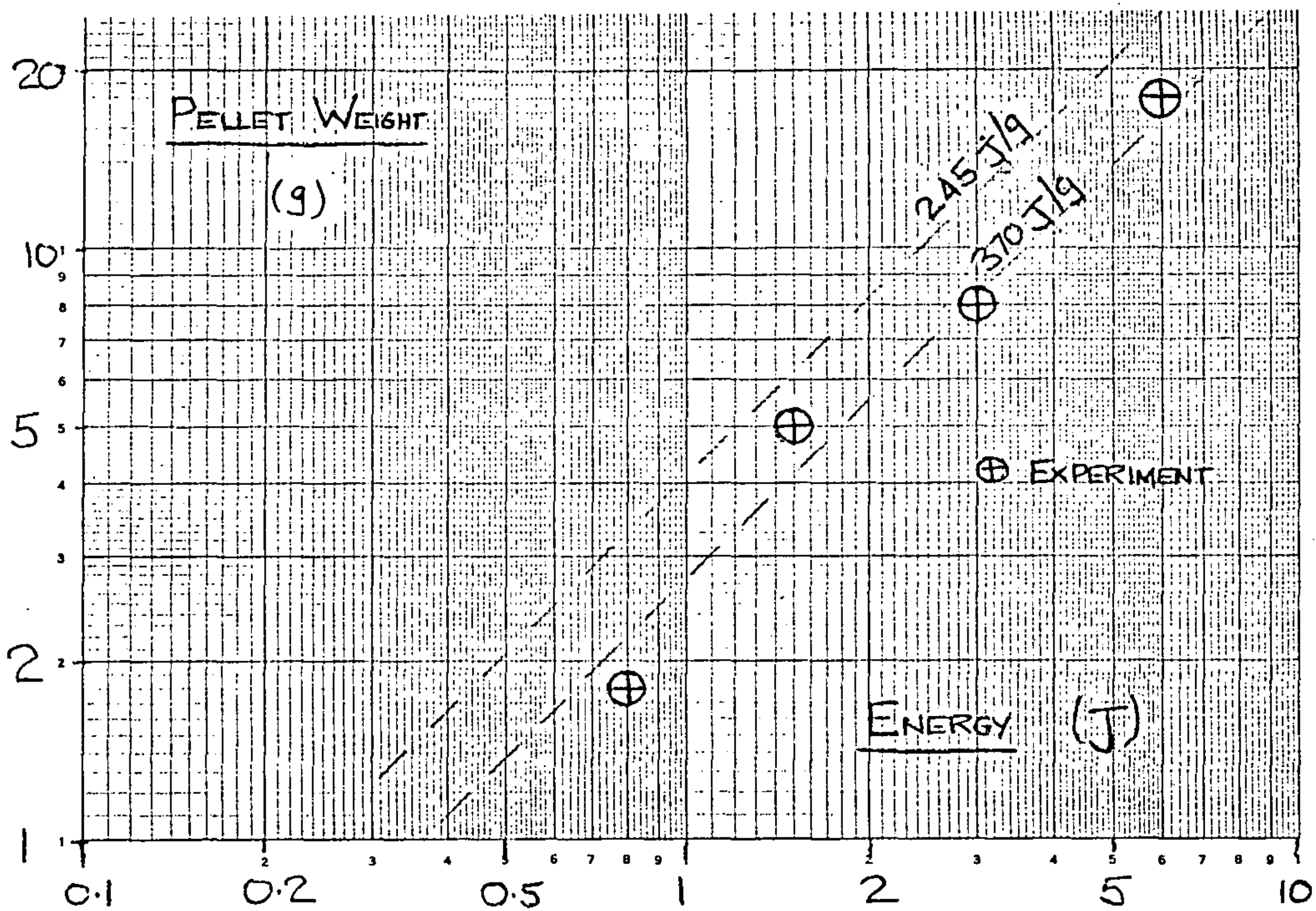


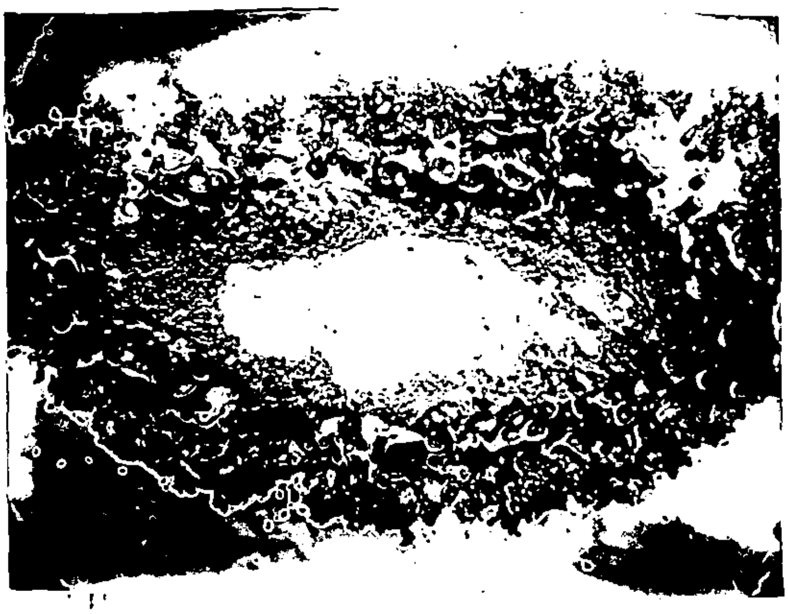
FIG. 7.3.9 PELLETING TEST RESULTS

(a) Typical Spot from Region 'B' (x90)

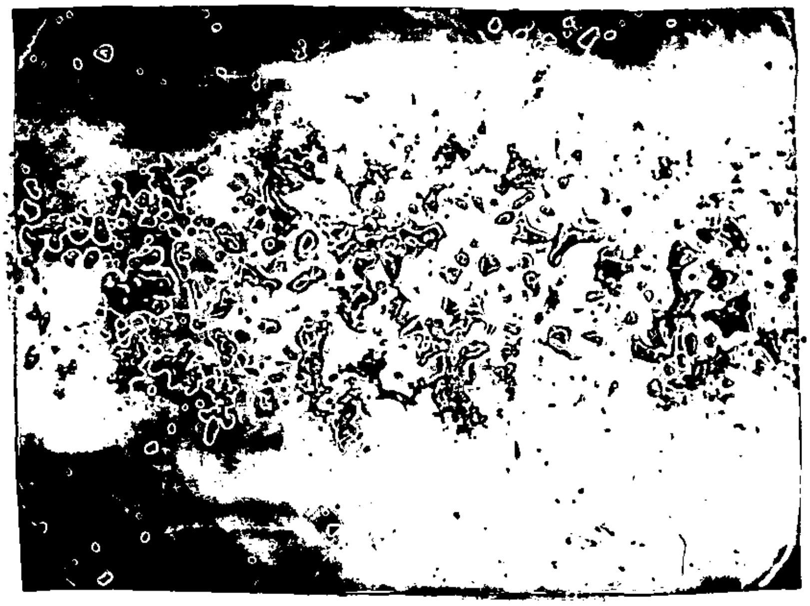
(b) Typical Spot from Region 'C' (x90)

Fig. 7.3.10 Microphotographs of Fused Ink Spots

(c) Typical Spot from Region 'D' (x90)



(d) Typical Spot from Region 'E' (x90)



(e) Typical Under-Inked Spot (x90)

(f) Typical Spot Produced by Chopping (x90)

12.0 References

Section 2

2/1 BABBAGE, C. "Charles Babbage and his Calculating Engines",Ed. P.E.Mirrison,Dover, New York (1961)

2/2 JOSEPHSON, M. "Edison",p68, Eyre and Spotiswood, London (1961)

2/3 EDISON, T.A. "Laboratory NotebookforSept.15th 1872"E.L.A. (from 2/2 above)

2/4 HIGGINS, "Type Printing Telegraph Instruments", Engineering, April 13th, p291 (1877)

2/5 WORCESTER, D.K. "Electrical Communications and the New York Stock Exchange",Elect. Engg. v50,n4,p255,(1931)

2/6 PIERCE, R.E. "Private Wire Telegraph Service", Elect. Engg. v50, n1, p45,(1931)

2/7 PIERCE, R.E. "Communications by Police Teletypewriters", Elect. Engg. v51, n8, p550, (1932)

2/8 HARTREE, D.R. "The ENIAC, an Electronic Computing Engine", Nature, v158, n405, p500, (1946)

2/9 WILKES, M.V. "The ENIAC High Speed Electronic Calculating Machine", Electronic Engg. v19, n230, p105 (1947)

2/10 HALEY, A.C.D. "DEUCE, a High Speed General Purpose Computer", Proc.I.E.E. v103B Sup. 2,p165, (1956)

2/11 LONSDALE, K.& WARBURTON, E.T. "Mercury-a High Speed Digital Computer", Proc.I.E.E. v103B Sup.2,p174, (1956)

2/12 ELLIOTT, W.S.,OWEN,C.E., DEVONALD, C.H.,& MAUDSLEY, B.G. "The Design Philosophy of Pegasus -a Quantity Production Computer",Proc.I.E.E. v103B Sup.2, p188, (1956)

2/13 KILBURN, T. "The University of Manchester Universal High Speed Digital Computer Machine", Nature,v164,n4173, p684, (1949) 2/14 MELINKOU, V.A. " The High Speed Electronic Computer at the Soviet Academy of Sciences (BESM)", Proc. I.E.E. v103B Sup.2, p280, (1956)

2/15 Anon. "The IBM 7010 Data Processing System", Data Processing, v5, n6, p364, (1963)

2/16 ROYLE, G.D. "Discussion on Peripheral Equipment" Proc. I.E.E. v106B, p458, (1959)

Section 3

3/1 DAVIE, W.A.J. "High Speed Printers", J.Brit.I.R.E. Sept. p675, (1960)

3/2 MASTERMAN, E. & PRESSMAN, A. "A Self checking High Speed Printer", Proc. Eastern Joint Computer Conference, A.I.E.E.E. p22, (1954)

3/3 GREENBLOTT, B.J. "A development study of the print mechanism of the IBM 1403 chain printer", Trans. A.I.E.E.E. I v81, p500, (1962)

3/4 Anon. "The Potter 3502 Printer", Electronics, v38, p128, (1965)

3/5 LUCAS, J.H. "A High Speed Stylus Printing System", Proc. I.E.E. v106B, p456, (1959)

3/6 BROOKE-WAVELL, B. "New Computer Output Recorders", Brit. Communications & Electronics, v5, p928, (1958)

3/7 THOMAS, F.R. "A High Speed Serial Printer", Proc. I.E.E. v106B, p457, (1959)

3/8 WALLENS, A.W. "A Novel Computer Output Printer", Brit. Communications & Electronics, v9, p518, (1962)

3/9 SCARROTT, G.G. & FREER, J.A. "A High Speed Line Printer using Optical Methods", Proc.I.E.E. v106B,p455, (1959)

3/10 Anon. "Ultra High Speed Printout Mechanism", Control, p111, (1963) 3/11 OLDEN, R.G. "A thin window C.R.T. for High Speed Printing with Electrofax",R.C.A. Review, v18, n3, p343, (1957)

3/12 OLDEN, R.G. "High Speed Printing on Electrofax", R.C.A. Review, v22, n3, p582, (1961)

3/13 JONES, E.D. "Character Generators for Digital Computers", Electronics, v33, n7, p117, (1960)

3/14 YOUNG, C.J. & GREIG, "Electrofax Rirect Electrophotographic Printing on Paper", R.C.A. Rev. v15,p469, (1954)

3/15 AMICK, J.A. "A Review of Electrofax Behaviour", R.C.A. Review, v20, n4, p752, (1959)

3/16 AMICK, J.A. "A Volume-charge Capacitor Model for Electrofax Layers", R.C.A. Review, v20, n4, p770, (1959)

3/17 HAUFFE, K."Electrophotographic Properties of Zinc Oxide", J. Photographic Science,v10,n6, p321, (1962)

3/18 AXFORD, & GILBERT, "Characteristics of Electrophotographic Papers", J.Phot.Science,v12,n1,p93, (1964)

3/19 Anon. "Message Printer (S.C.3070)", Data Processing, v5, n4, p218, (1963)

3/20 REDMAN, J.H. "Advanced Display techniques through Charactron shaped beam tube", Society Information Display Symposium, 14th March (1963)

3/21 McNANEY, "Electron Gun Operates High Speed Printer", Electronics, v31, n39, p74, (1958)

3/22 HUNTLEY, K.G. & HUGHES, J. "Some Aspects of Xerographic Data Printers", Proc.I.E.E. v106B, p454, (1959)

3/23 PETERSON, R.M. & RITCHART, R.C. "Recent developments in shaped beams and recording techniques", I.R.E. National Convention Record,part 3, p21, (1958) 3/24 STILLWELL,P.F.T. & DAGNELL,R.H. "Xerography Applied to a High Speed Computer Printer", Electronic Engineering, v36, p756, (1964)

3/25 Anon. "Xerographic Pin Tube Recorder", Battelle Tech. Review, v7, n6, p15, (1958)

3/26 Anon. "Electrostatic Printing (A.B.Dick 905)", Data Processing, v2, n2, p84, (1960)

3/27 CREWS,R.W. & RICE, P. "The Videograph Tube - a new component for high speed printing", I.R.E. Trans. Electron. Devices, vED8, n5, p406, (1961)

3/28 WEST,R.E. "High Speed Readout for Data Processing", Electronics, v32, n22, p83, (1959)

3/29 KIEL,K.M. "High Speed Terminal Printers", Electrical Engineering, October, p1026, (1959)

3/30 FAHNSTOCK,J.D. "High Speed Printer for Weapons Testing", Electronics, v29, n9, p166, (1956)

3/31 GETTINGS,H.W. "Digital Printer Boosts Readout Time", Electronics, v30, n6, p182, (1957)

3/32 Anon. "High Speed Computer Output Printer", Data Processing, v6,n1, p46, (1964)

3/33 SEEHOF, J. et Al. "The N.C.R. Magnetic Printer", Proc. Eastern Joint Computer Conference (I.R.E.-A.C.M.-A.I.E.E.) Washington, 9th-13th December, p243, (1957)

3/34 UEMURA, MATSUMOTO, &MURAMOTO, "high Speed Magnetic Printer" (Abstract only) E.T.J. (Japan) v7, n4, p149, (1962)

3/35 S.T.L. "The Ferrodot System (Standard Telecommunications Laboratories)", Physics Exhibition Cat. London,April(1967)

3/36 GREIG,H.G. "The Chemistry of High Speed Electrolytic Facsimile Recording", Proc. I.R.E. v36, p1224, (1948)

Section 5

5/1 CARLSON, C.F. "U.S. Patent No.2,297,691",4th.April,(1939)

5/2 CARLSON, C.F. "U.S. Patent No.2,357,809"16th.Nov.(1940)

5/3 NEWMAN, A.A. "The Science and Art of Xerography", Brit. J. Phot. p784/p804/p828, (1964)

5/4 DINSDALE, A. "Chester F. Carlson-Inventor of Xerography a Biography", Phot. Sci. & Engg. v7, n1, p1, (1963)

5/5 DESSAUER,J.H. MOTT,G.R. & BOGDONOFF,H. "Xerography Today" Photographic Engineering, v6, n4, p250, (1955)

5/6 CLAUS,C.J. "Advances in Xerography 1958-1962", Phot. Science and Engineering, v7, n1, p5, (1963)

5/7 PERRY,K.E. & AHO, E.J. "Generating Characters for C.R.T. Readout", Electronics, v31, n1, p72, (1958)

5/8 MOORE,J.K. & KRONENBERG,M. "Generating High Quality Characters", Electronics, v33, n24, p55, (1960)

5/9 GRIMSDALE,R.L. & BARRACLOUGH,M. "A C.R.T. Output for a Digital Computer", J.Brit.I.R.E. v21, n6, p497, (1961)

5/10 Anon. "C.R.T. Character Generation", Brit. Communications and Electronics, v9, p531, (1962)

5/11 KIME,F.W. & HARTLEY-SMITH,A. "Data Display System works in Microseconds", Electronics, v36, n48, p26, (1963)

5/12 BOYD,S.H. "Digital-to-Visible Character Generators", Electro-Technology, v75, n1, p77, (1965)

5/13 SPIRER,H.F. & MURRAY,F.V. "Digital Readout Devices", Electromech. Components & System Design,v10, n1,p169,(196[illegible]

5/14 BICKMORE,J.T. LEVY,M. & HALL,J. "High Resolution Xerography by Aerosol Development", Phot.Sci.&Engg. v4, n1, p37, (1960)

5/15 DESSAUER,J.H. & CLARK,H.E. "Xerography and Related Processes", Focal Press, London, (1965) 5/16 SCHAFFERT,R.M. "Electrophotography",Focal Press,Lond.(1965)

5/17 STARR,A.T. "Xerography", J.I.E.E. p592, December, (1962)

5/18 BICKMORE,J.T. & ETT, A.H. "Xerography for Close Access Recording of Continuous Tone Line Scan C.R.T. Presentations" Phot. Science & Engineering, v5, n3, p136, (1961)

5/19 RAYFORD,R.E. & BIXBY,W.E. "Reversal Development of Continuous Tone Xerographic Images",Phot.Eng.v6,n3,p173(1955)

5/20 KAPRELIAN,E.K. & LEINSTER,K."The Signal Corps Role in the Development of Continuous Tone Xerography",I.R.E. Trans. Military Electronics, vMIL4, n4, p591, (1960)

Section 7

7/1 PATEL,C.K.N. "C.W. High Power N_2/CO_2 Laser", Applied Physics Letters, v7, n1, p15, (1965)

7/2 BRIDGES,T.J. & PATEL,C.K.N. "High Power Brewster Window Laser at 10.6μm", Appl. Phys. Letters,v7,n9,p244,(1965)

7/3 MOELLER,D. & RIGDEN,J.D. "CO_2 Lasers", Appl. Physics Letters, v7, n10, p274, (1965)

7/4 PATEL,C.K.N. TIEN,P.K. & McFEE,J.H. "C.W. High Power CO_2/N_2/He Laser", Appl. Phys. Lett. v7,n10,p290, (1965)

7/5 CARSLAW,H.S. & JAEGER,J.C. "Conduction of Heat in Solids" 2nd. Edition, Oxford, (1959)

7/6 GUENOT,R. & RACINET,J. "Heat Conduction Problems in Laser Welding", Brit. Welding J. v14, p427, (1967)

7/7 VAN NOOD,J.H. & BEEK, W.J. "Radiative Heat Transfer to continuously Moving Thin Metal Plates", Chemical Engg. Science, v21, p851, (1966)

7/8 COBBLE,M.H. "Finite Transform Solution of the Temperature of a Plate Heated by a Moving Discrete Source", Int. J. Heat & Mass Transfer, v10, p1281, (1967)

7/9 LUIKOV,A.V. SHASHKOV,A.G. VASILIEV,L.L. & FRAIMAN,Yu.E. "Thermal Conductivity of Porous Systems", International J. Heat and Mass Transfer, v11, p117, (1968)

7/10 CLINE,D. & KROPSCHOT,R.H. "Thermal Properties of Powder Insulators", Radiative Heat Transfer from Solid Materials, (Ed. Blau,H. & Fischer,H.)p61, MacMillan, New York (1962)

7/11 BRODIE,D.E. & MATE,C.F. "Heat Transfer in Gas Filled Powders at Low Temperatures", Can.J.Phys.v43,p2344,(1965)

7/12 VAN DER HELD,E.F.M. "The Contribution of Radiation to the Conduction of Heat", Appl.Sci.Res.Sect.A,v3,p237, (1953)

7/13 MURRAY,W.D. & LANDIS,F. "Numerical and Machine Solutions of Transient Heat Conduction Problems Involving Melting or Freezing", Trans.A.S.M.E. v81, Ser.C,p106, (1959)

7/14 GOODMAN,T.R. "The Heat Balance Integral and its Application to Problems Involving Change of Phase", Trans. A.S.M.E. v80, p335, (1958)

7/15 LOCKWOOD,F.C. "Simple Numerical Procedure for the Digital Computer sol.of Non-Linear Transient Heat Conduction with Phase Change",J.Mech.Eng.Science, v8, n3, p259, (1966)

7/16 BOLEY,B.A. "A Method of Heat Conduction Analysis of Melting and Solidification Problems",J.Maths.&Phys.v40,p300,(1961)

7/17 BOLEY,B.A. "Upper and Lower Bounds for the Solution of a Melting Problem", Quart.of Appl. Maths.v21,n1,p1, (1963)

7/18 PENNER,S.S. & SHARMA,O.P. "Interaction of Laser Radiation with Absorbing Semi-Infinite Solid Bar", J. Applied Physics, v37, n6, p2304, (1966)

7/19 HAJI-SHEIKH,A. & SPARROW,E.M. "The Solution of Heat Condn.Problems by Probability Methods",Trans. A.S.M.E. J. Heat Transfer, May, p121, (1967) 7/20 DICKER,D. & ASNANI,M. "A Perturbation Solution for the Non-Linear Radiation Heat Transfer Problem", Proc. Int. Heat Transfer Conf.A.S.M.E.(Chicago) v5, p164, (1966)

7/21 LIEBMANN,G. "A New Electrical Analog Method for the Soln. of Transient Heat Conduction Problems",Trans.A.S.M.E. v78, p655, (1956)

7/22 LIEBMANN,G. "Solution of Transient Heat Transfer Problems by the Resistance Network Analog Method", Trans. A.S.M.E. v78, p1267, (1956)

7/23 Anon. "Directional Control of Laser Beams", Brit. Comm. and Electronics, v11, p265, (1964)

7/24 CARLETON,H.R. & SOREF,R.A. "Modulation of 10.6µm Laser Radiation by Ultrasonic Diffraction", Applied Physics Letters, v9, n3, p110, (1966)

7/25 DIXON,R.W. & CHESTER,A.N. "Acoustic Light Modulation for 10.6µm", Appl. Physics Letters, v9, n5, p190, (1966)

7/26 WALSH,T.E. "Gallium Arsenide Electro-Optic Modulators", R.C.A. Review, v27, n3, p323, (1966)

7/27 PETERS,D.W. "Infrared Modulator",Appl.Optics,v6,n6,p1033 (1967)

7/28 BEISER,L. "Spot Distortion During Gradient Deflection of Focussed Laser Beams", I.E.E.E. J.Q.El.vQE3,n11,p560,(1967)

7/29 KAMINOW,I.P. "Measurements of the Electro-Optic Effect in CdS, ZnTe, GaAs, at 10.6µm", I.E.E.E. J.Q.Electronics, vQE4, n1, p23, (1968)