# RESEARCH AND DEVELOPMENT OF CATHODE RAY TUBES

FINAL REPORT

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# RESEARCH AND DEVELOPMENT OF CATHODE RAY TUBES

FINAL REPORT

THE PURPOSE OF THIS RESEARCH AND DEVELOPMENT CONTRACT IS THE APPLICATION OF INTERNAL ELECTROSTATIC YOKES, OR "DEFLECTRONS", TO VARIOUS TYPES OF WIDE ANGLE, HIGH INTENSITY TUBES, INCLUDING RADAR AND CHARACTRON DISPLAYS.

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The same tube was then re-assembled with the adress-Deflectron rotated forward by the 6 degrees found from the vacuum test. The RF-jig was used to establish the new position of the yoke.

When the gun was tested, again, in vacuo, the error was completely eliminated, and the axis of both yokes were in perfect alignment.

It is concluded, from this experience, that the RF-jig can be used for gun assembly, even in cases where there is no numerical agreement between the RF-analog and the tube. In such cases, the difference between the two is measured once and for all, and the analog is then preset to take care of it.

## 6.0 Phase 6 - An Electrostatic Character-Writing Tube

Items (i and j) of the contract specifications required an investigation of the feasibility of using Deflectrons for the construction of a character-writing tube, to be partly or fully electrostatic in operation. An advantage of the electrostatic approach consists in the absence of external magnetic fields and of image rotation, as well as the low power required for, and the high speed of, electrostatic character selection and distribution.

In the course of our work, it soon became apparent, that an entirely electrostatic tube of this type was practical. The end-result of this development is henceforth briefly referred to as "Printoscope".

It represents a successful application of the Deflectron-principle to complex cathode-ray displays.

## 6.1 Basic Elements of the "Printoscope"

Figure 6-1a shows the basic elements of an electrostatic character writing tube. The gun-section comprises 6 essential components:

A. electron gun

B. selecting Deflectron

C. collimating section and matrix

D. restoring Deflectron

E. image forming section

F. adress Deflectron

Of these, items (C) (collimator) and (E) (image-former) posed new problems, whose development will be treated below. For the remaining items, available components could be used, as described in the preceding sections of this report. This included the adress Deflectron, which used the type CO2-86 with wide input aperture (see Phase 3, par. 3.0), as well as the mask and screen assembly, for which a Barrier mask accelerator was employed (See Phase 2-par. 2.0).

## 6.2 The Collimation-problem

In Figure 6-1a, the function of the collimator is symbolized by two lenses (3), arranged before and after the matrix. The latter consists of a thin sheet of nickel-plated copper (.003 inch) with 63 character-perforations, as shown in detail in Figure 6-2.

6.2.1 Collimation by electron-lenses

Character selection is accomplished by a first Deflectron #2, which deflects the beam by an angle $\alpha$ in any arbitrary plane through axis (plane of paper). The job of normalizing the beam prior to passage through matrix, and then returning the "shaped" beam to axis, can conceivably be done by two electro-static electron-lenses (3), whose focal length equals their distance from the centers of deflection of the selecting Deflectron (2) and the restoring Deflectron (4), respectively[24]. Equal deflection-factors in (2) and (4) would then permit interconnection of corresponding terminals, thus resulting in a simple 4-terminal electrostatic device for matrix read-out and collimation.

Unfortunately, our early experiments with this type of lens-collimator indicated clearly, that conventional electrostatic lenses are inadequate for this purpose. When designed to meet the high requirements of precision and freedom from spherical aberration, the lens-type collimator becomes too long and too bulky to be practical.

6.2.2 Collimation by electron-prisms

Before reporting about these tests in more detail, we present in Figure 6-1b the "conjugate-prism" approach, which was ultimately successful. Here, the collimating action is supplied by two separate Deflectrons B and C, which have equal deflection-factors, but much larger apertures, than the first and last Deflectron A and D of the read-out unit. To a first approximation, equal sensitivity of all four yokes is assured by equal length-to-diameter ratio throughout the chain. The voltage sensitivity of a Deflectron is given by:(*)

$$e_{\Delta} = 25 d_m / \ell \quad \text{volts per KV} \bullet \text{degree} \tag{6-B}$$

where $e_{\Delta}$ is the signal voltage per terminal, and $d_m$ the mean diameter of the yoke. The four Deflectrons (A) through (D), shown in Figure 6-16, have $d/\ell$ ratios of 1 to 1. Hence, they can all be interconnected to form a complete selector unit with 4 terminals.

The optical analog of this structure is a string of double-prisms, all units bonded together, but the whole group free to rotate around the tube axies. If the electrical axes of all four Deflectrons are aligned for coincidence the same plane of deflection is common to all.

In view of the first-order linearity of deflection angle with voltage, and of the relatively small total angles involved ( $2\alpha \leqslant 16^{\circ}$ ), this double-prism approach can be expected to give satisfactory performance, even if designed for short overall length. This has been borne out by experience.

## 6.3 Early developmental tubes

The following is a more detailed historical account of the steps

* This equation is derived in Reference No. 1.

taken during the development of the "Printoscope". The report includes the character selector unit and also the image forming section, whose design is influenced by the electron-optics of the selector unit.

6.3.1 Collimation by lenses

The function of the collimator units $C_1$-$C_2$ in Figure 6-3a is similar to that of ideal electron lenses, whose focal points coincide, respectively, with the deflection centers of $D_1$ and $D_2$. Accordingly, our first approach to the problem was to try uni potential lenses, made of coaxial cylinders. Figure 6-3b shows an early test setup, using a lens-type collimator.

The test comprised an electron gun (1) a first lens (2), and a pencil Deflectron (3) type CY1-33 as first prism. The collimator was a barrel lens, having two inner tubes (4) (5) at anode potential (zero) and an outer cylinder (6) at controlled negative potential. Since deflection angles up to $20^{\circ}$ were under consideration, the lens aperture had to be large (1-1/4 inches) to minimize spherical aberration.

The actual test of the barrel-lens collimator soon revealed some difficulty in obtaining the required short focal length without excessive bias-voltages. With the large lens opening required by spherical aberration, the desired focal length is only about 1.5 lens diameters. This required excessive negative barrel voltages, several kilovolts below cathode, for a 2 KV beam.

In a practical test, switching the barrel electrode (6) from anode to cathode potential, caused a deflection loss, for a stationary spot on the screen, of 30%. ($K = Y_2/Y_1 = 0.7$)

From this data, and from the known image-to-object spacing ($b = 3\text{-}3/8$ inches, $a = 3\text{-}5/8$ inches), the focal length f was found as follows:

$$1/f = (1-k)\,(1/a + 1/b) \qquad 6\text{-}2$$

The result was: f = 8-1/2 inches; i.e. a lens "speed" of O/F = 1-1/4:8-1/2 = 1:7. It was concluded, that with lenses of this low F-number, the tube would be too long to be practical. Other deterrents against the use of lenses are their size and weight (185 grams when made of aluminum), noticeable spherical aberration, and critical centering and alignment problems.

It was therefore decided to abandon the use of lenses as collimators, and to use prism-optical systems instead.

6.3.2 Collimation by electrostatic prisms

To test the feasibility of collimation by anti-deflection (prism-optics), a simple tube was built, as shown in Figure 6-4. In order to speed up construction and simplify alignment, this system was one-dimensional; i.e. Deflectrons were replaced by parallel pairs of plates, pairs of plates of equal D/L ratio. When used in a circuit as of Figure 6-5, it was possible to adjust the signal for the collimating units $D_2D_3$

on a ganged voltage divider $R_2R_3$, while characters were selected by the voltage $E_s$ fed to the units $D_1D_4$. This tube could not read the matrix in full, but only one center line of it. However, the test yielded some advance-information for a system of cylindrical Deflectrons, having the same cross section in the z, $r$ -plane as the sample.

This tube projected images of 0. 200 inch on a screen 26 inches behind the second lens $L_2$. These images could be focused by $L_2$. Their size was about 0. 300 inch which is somewhat larger than anticipated by optical considerations (distance ratio: 13 to 1; original letter-size: 016 inch, Fig. 6-2.)

The picture quality of this early tube (Fig. 6-6) was somewhat marred by hum, due to the wide-open gun structure and the absence of electrostatic shields.

More than one letter at a time appeared, unless the condensor lens $L_1$ was properly focused. In this process, image brightness increased, but readability decreased sharply, when $L_1$ was overfocused to produce a crossover in the plane of the matrix.

Figure 6-6c shows the selector in transit between two adjacent characters. It is obvious, that the images were "rolling" into position, instead of "blending" into each other without changing places. This "fixed-focus" condition, which is very desirable, will be discussed in par. 6. 4 of this section.

When operating the tube, it was found, that there was only one critical setting of the ganged voltage dividers $R_2R_3$, which resulted in keeping all character images centered on tube axis. This image immobilizing occurred, if the voltage admitted to the collimator plates $D_2$ $D_3$ was 90% of the voltage used for the selector units $D_1$ $D_4$.

On the whole, this early test clearly indicated the potential usefulness of the prism-optical approach, and its superiority over the use of lens-collimators, as tried before. It was then decided to proceed to a 2-dimensional form of this tube, and to develop the sets of conjugate Deflectrons required for it.

6.3.3 First deflectronized "Printoscope"

Figure 6-7 shows a photograph of the first fully deflectronized "Printoscope", as tested in the demountable. Figure 6-8 gives the dimensional data for this gun, including the prospective mask-and-screen section, which was not included in these early tests.

It will be seen, that this tube used 4 separate cylindrical Deflectrons for character selection. All of these units were "conjugate" i.e. their deflection factors were identical. (25 volt per kilovolt degree).

Each unit had a D/L ratio of 1 to 1, with the two small "A-D" units having an I.D. of 1/2 inch and the two large "B-C" - units an I.D. of 1 inch. The printing on all 4 cylinders was a so-called "basic-sinusoid" pattern having two, and four, halfwave-cycles on units AD and BC, respectively. Because of the small angles involved, this simple, uncorrected pattern has proven adequate through the entire line of development.

For the electrical alignment of Deflectrons, an electronic jig, or "Pole-detector" was used, as described in par. 5.0 of this report. An 18 inch micalex rod of 1/4 inch diameter carried the dipole-antenna used. Figure 6-8 shows that this probe could be inserted as far down the second anode of the gun-assembly. Thus all 5 Deflectrons, including collimation and adress, could be electrically aligned with each other.

In an effort to reduce the image size, a 2 inch drift tube((S) in Figure 6-8) had been inserted between the selector-output and the thin "Einzel" lens $L_2$. This doubled the object-distance over the previous test-tube (Fig. 6-5). The expected image magnification now was 4:1. However, the observed electron images still were consistently between 3 to 4 times larger! We suspected this to be in part due to excessive spherical aberration. Figure 6-9 shows electron images of a mesh (.020 holes, .030 between centers) taken with these early lenses. All holes in the original had equal diameters.

Another interesting experience was the influence, on image quality, of adjustments made in the electron gun, used to illuminate the matrix.

Figure 6-10 tries to illustrate this point. It shows the exit aperture of the gun, ($L_1$), projecting a beam towards the matrix (M). By adjusting the condenser lens, or "first" lens ($L_1$) in the gun, the beam could be focused either on the near side of the matrix (point NF), or on the far side of it (point FF). In both conditions the area of illumination on the matrix could be confined within the area required for selection of a single character. In the near focus mode, the condenser-lens electrode $L_1$ was held at 32 percent of anode voltage $A_{12}$. In the far focus mode, the condenser-voltage was 45 percent of anode.

It was found, that the near focus ($F_N$) mode was superior in image quality and ease of character selection, but gave slightly larger images than the far-focus ($F_f$) mode. The latter gave brighter and smaller images, but exhibited less resolution, more scanning defects, and more "spillover", or crosstalk, from adjacent characters. When the crossover was made to coincide with the matrix, a bright "ball of fire", but no image, appeared when illuminating a character. Table 9 is a listing of the adjustments made on this early tube.

In this tube, the character-selector unit seemed to function properly. However, the images still showed signs of spherical aberration, and their actual size was about 5 times larger than expected.

6.3.4 The second developmental "Printoscope"

This tube is shown in the photo of Figure 6-11; a blueprint of it is given in Figure 6-12.

Table 9 - Data Observed on Test-Tube of Figure 6-8

object distance: 5.5"  object size: 0.4 mm
image distance: 24"  expected image size: 1.7 mm
distance ratio: 4.35 to 1  Anode voltage: 2.200 volt

Observations

A: near focus mode: Condenser lens at: $L_1/A_{12}$ = 0.32.

| Test # | Second Lens $L_2/A_{12}$ | Observed Image Size (mm) | Image Position | Observed Magnification | Resolution | Remarks |
|---|---|---|---|---|---|---|
| 1 | 0.32 | 25 | inverted | -62 | poor | generally good character selection, no spillover, reads full height of matrix |
| 2 | 0.41 | 13 | inverted | -32 | fair | |
| 3 | 0.50 | 5 | inverted | -12 | good | |
| 4 | 0.58 | 3 | focal spot | --- | --- | |
| 5 | 0.68 | 7 | upright | +15 | very good | recommended adjustment |
| 6 | 1.00 | 11 | upright | +27 | good | |

B: far focus mode: Condenser lens at: $L_1/A_{12'}$ = 0.45

| Test # | $L_2/A_{12}$ | Observed Image Size (mm) | Image Position | Observed Magnification | Resolution | Remarks |
|---|---|---|---|---|---|---|
| 7 | 0.23 | 18 | inverted | -45 | bad | scans only one-half matrix-height tendency to spillover, showing adjacent letters. |
| 8 | 0.36 | 9 | inverted | -22 | good | |
| 9 | 0.45 | 4.5 | inverted | -11 | very good | |
| 10 | 0.68 | 2 | Focus | --- | --- | |
| 11 | 1.00 | 3 | no image | +7.5 | --- | |

The selector section of this tube is not much altered over the previous gun, and it still uses 4 separate conjugate Deflectrons for character selection. However, major changes were made in the image forming unit.

#### 6.3.4.1 Large lens-barrel

First an effort was made, to reduce the spherical aberrations in the imaging lens $L_2$, which had marred the performance of earlier tubes.

Proof that the original lens $L_2$ (structure $L_2$, Fig. 6-8) was inadequate, was obtained by slipping a short magnetic lens over the neck of the early tube and electrically disabling the built-in electro-static lens. An excellent image was obtained with the magnetic lens. After this test, an effort was made to develop a better electro-static lens.

The obvious approach was to attempt a reduction of the spherical aberration in $L_2$ by increasing its diameter as much as possible within a 2 inch neck. A diameter of 1 1/4 inches was chosen for the new lens. Since the spherical aberration decreases with the third power of radius, the expected improvement over the previous tube (1/2 inch diameter) is $(1\ 1/4 : 1/2)^3 = 16$ times.

Various lens structures were tried, some using two component-cylinders at different voltages. The end-result of these tests indicated that a single large cylinder between flat discs was doing as well as the best composite structures. (See $L_2$ in Fig. 6-11)

6.3.4.2 Size Control

Consideration was then given to size control of the image. The primary object at this stage of development was permanent adjustment, rather than fast switching, of letter size.

If it is possible to define the position of an equivalent thin lens, it can be shown that the size of the electron image of a given object is determined by the "transit-time rule".[20] This law states that the electron-optical magnification equals the ratio of transit times through image and object space, respectively.

$$m = \frac{T_i}{T_o} \qquad 6\text{-}4$$

In the simple case that both spaces are "drift" spaces of path length a and b, and that the electron volts in each are, $e_a$ and $e_b$, respectively, equation 6-4 takes the familiar form:

$$m = \frac{b}{a} \cdot \sqrt{\frac{e_a}{e_b}} \qquad 6\text{-}5$$

This form indicates that, even if the tube dimensions (a) and (b) are given, the image size can be changed, by adjusting the electron velocities in object and/or image space.

Figure 6-13 shows how this "transit-time rule" can be applied to the Printoscope. The object distance (a) is given by design conditions governing the selector-section. The image distance (b) is the "pencil-length", and is determined by bulb shape and sweep angle. The desired magnification is 12.5. This would yield letters of .200 inch from objects of .016 inch in the matrix. The structural distance-ratio (Fig. 6-12) is $21/4.2 \approx 5$ to 1. The balance of $12.5/5 = 2.5$ to 1 can be supplied by deceleration in the image space as given by equation 6-4. To this end, the voltage in the image space (inside the bulb) must be reduced over the voltage in the object space (selector-section) by a factor of $(1/2.5)^2 = 0.16$. Any change of this voltage ratio in one sense results in a change of image size in the opposite sense. Hence, the voltage in the drift space can be used for the purpose of size-adjustment.

In practice, this requires the DAG-coating of the funnel section to be kept electrically apart from the shield around the neck-section, housing the character selector and gun.

Figure 6-13 shows the voltages applied to successive electrodes of the Charactron, including the decelerating lens $L_2$ and the voltage reduction from 6000v in the selector section ($A_{12}$) to about 1500v in the drift space ($A_d$). The drift space is terminated by a barrier mask. This BMA makes it possible to apply full ultor voltage (20,000v) to the screen, while offering flexibility in the choice of voltages used in the deflection-space. The BMA readily permits post-acceleration ratios between 10 and 15 to 1.

Figure 6-13 also shows the general circuit layout to go with transit-time control of size. It will be noticed that the system may be grounded simultaneously at two places, namely:

- at the cathode
- at the address-amplifier

The adress amplifier is DC-coupled to the adress-yoke, in order to permit scanning with complex waveform. For the same reason, it is convenient to have its control grids near ground, since this permits the use of low-level clamping circuits. The funnel potential $A_d$ is derived from the adress-yoke through 4 bleeders $R_d$. In this manner, the IR drop in the plate load of the address amplifier can be used for part or all of the deceleration required by the electron-optical system. Figure 6-13 further shows that the tube-cathode is at ground. This simplifies design and operation of gating and keying circuits for the first grid.

At this point, it should be mentioned that this method of size-adjustment is not intended for fast switching, but is suitable only to adjust, more or less permanently, a preferred range of magnification.

#### 6.3.4.3 Performance Data

Figure 6-14 is a photo of images obtained with deceleration ratios of 1/1, 1/1.9, and 1/2.75, respectively between character-selector and funnel section. The black rulings on the screen are 1 inch apart.

Figure 6-15 shows the measured image size as a function of deceleration. When using, as abscissa, the square root of the voltage ratio ($A_2$:$A_d$), these curves are indeed straight lines as required by theory (equation 6-5). Magnification control by deceleration has been accomplished over a range of 1.7 to 1. In these tests, the image size ranged from 85 mils to 145 mils, corresponding to magnification ratios of 5 through 9.

The above tests were made in a demountable using an open accelerator (Fig. 6-16b). In the barrier mask accelerator (BMA) (Fig. 6-16a) the image size will be twice as large. This is due to the fact that the electron velocity in the BMA is constant and small throughout the image space. Hence, the transit time $T_i$ in the BMA is longer than in the open accelerator, where electrons are gradually speeded up throughout the deflection space. The result is an increase of magnification in the BMA (equation 6-4). The particular value of 2 to 1 for relative letter-size has been extrapolated from measurements in the open accelerator, as shown in Figure 6-16c. Image sizes were measured on tube 6-16b for various values of Ultor voltage $E_u$, but with constant Dag-voltage Ed. The results were plotted in double-log paper as a function of the acceleration ratio $P = E_u/Ed$.

Figure 6-16c shows that all readings lie on straight lines with a slope of $19.5^{\circ}$. This indicates the magnification to decrease with the cube-root of P, or

$$\frac{m}{m_0} = \frac{1}{\sqrt[3]{P}} \qquad 6\text{-}6$$

To find the image size expected of future tubes with BMA, the graph of Figure 6-16c was extended to the ordinate P = 1, corresponding to electron drift through the bulb at constant speed. *)

It is seen, that the images in the BMA tube (Fig. 6-16a) will be just twice as large as those observed in the test tube(Figure 6-16b) run with 4500v on the screen, and 600 volt at the reference line, or P = 7.5 to 1.

On this basis, it was anticipated that other conditions equal, we will have magnification control between 10 and 18 to 1, and letter heights between .170 inch and .290 inch in our sealed-off Printoscopes using the barrier-mask accelerator.

6.3.4.4 Lens-bias modulation

When experimenting with the tube of Figure 6-11, another method for size-control was uncovered. It was found that considerable changes of magnification occurred with only slight changes of lens barrel voltage, other conditions being equal. Figure 6-17 shows the image quality obtained with tube 6-11/6-12 under 4 different conditions of operation: Figure 6-17a was obtained with the $L_2$ lens at 840 volt (38 percent of $A_2$ voltage). Figure 6-17b resulted from $L_2$ = 740 volt, or 33 percent of $A_2$. This method of size control by voltage modulation can be carried

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* It is interesting to compare equation 6-6 for magnification with the identical expression, derived in par. 1.0 (eq. 1-12) for deflection-loss in an immersion accelerator. Both equations are most readily derived by transit-time considerations. This lends support to the electron-ballistic approach to electron-optics, in preference to analogies with light-optics.

out at great speed and without supply of power, since no current flows into $L_2$. It is conceivable to switch from small to capital letter size in this manner thus obviating about one-third of the characters in the present matrix. However, a pre-requisite for this technique is excellent symmetry and alignment of the lens-barrel!

Condition C is the "far-focus" mode. The inferior quality of these images is obvious, when compared to the NF-mode (A and B).

Condition D occurs with heavy negative bias on $L_2$. In this condition, the first gap of the long barrel becomes sufficiently refractive to project a real, and inverted image inside the barrel, and ahead of the second gap. The latter acts as the imaging lens in the resulting "electron-microscope". Images now appear inverted and magnified about 62 times linear, or 4000 times in area.

During the final stage of this development, it turned out, that this "microscope"-mode of image-formation was the most suitable method for effective adjustment of letter-size (see below, under par. 6.4).

6.4 Final Phase of Printoscope-Development

The final phase of our development of an all-electrostatic character-writing tube culminated in the demonstration, in a 10" demountable, of a working model of the "Printoscope" (Fig. 6-26).

The test consisted in a high-frequency read-out of the entire matrix (Fig. 6-2) at a rate of 2430 characters per second. The demonstration included the BMA-accelerator section, operating with full 20KV-rating on the screen. The Printoscope-guns used represented the final stage of our development. They employed special "Tandem-Deflectrons", as well as a "Telescope" type of electron-optics, permitting effective size control. Two identical gun assemblies of this type have been built and operated, not counting several developmental units. Both "Printoscope" guns have given identical performance in the demountable.

### 6.4.1 Theory of Collimation by Deflectrons

Preparatory to finalizing the "Printoscope" development, it became necessary to review the principles of electrostatic collimation by Deflectrons. Since this analysis has guided the final design of the "Printoscope" it is presented below in greater detail.

In the "Printoscope", two parallel and opposite blocks of electric field are used to deflect and collimate an electron beam. Two pairs of such fields - each of them set-up inside a so-called "Tandem-Deflectron" are then combined to form a complete character-selecting unit. The operation of this system is based on certain properties of electrostatic deflection of oblique beams.

#### 6.4.1.1 Electrostatic deflection of oblique rays

6.4.1.1.1 One block of field

Figure 6-18 shows a cathode ray (1) from an inclined electron gun (2) entering into a block (3) of uniform electric field $\overline{E}$. The angle of incidence is $\alpha°$ for ray (1), and $\beta°$ for ray (4) leaving the block. This system is analyzed under the following simplifying assumptions:

- Fringe-field effects are neglected
- The ray is assumed to be filamentary
- Deflection is balanced; i.e. there is no major potential difference between anode voltage $V_A$ and space potential near the beam entrance.

It can be shown that:

A. All rays seem to come from the point of intersection (c) between the incident ray (1) and the center-plane (P) through the system.

B. The actual deflection $\Delta$ observed on a plane screen (5) is strictly proportional to the deflection voltage ($V_d$).

C. The deflection factor increases with the angle of incidence as indicated by equation 6-7

$$\Delta = \frac{1}{2} \frac{V_d}{V_a} \cdot L \cdot \frac{1}{\cos^2 \alpha} \tag{6-7}$$

These statements are not restricted to small deflection-angles or normal incidence.

Proof of (A) is elementary since it holds for any trajectory of parabolic shape. The equations of motion predict that the beam will follow a curve of the general form:

$$y = a + bz + cz^2 \qquad \text{6-8}$$

It can be shown by simple analytic geometry that the tangents from both ends of the block meet at the mid plane P-P, which thus turns out to be the "principal plane" of the device.

Proof of (B) proceeds as follows: Accepting statement (A), we can read off Figure 6-18:

$$\Delta = L\left[\tan\alpha - \tan\beta\right] \qquad \text{6-9}$$

Here, L is the pencil length from mid-field to screen, and $\alpha$ and $\beta$ are the inclinations, off-normal, before and after deflection. Replacing angle-functions by velocity-components, we get

$$\Delta = L\,\frac{\dot{y}_e - \dot{y}_o}{\dot{z}_o} \qquad \text{6-10}$$

From the equation of motion

$$\mu\ddot{z} = 0 \qquad \text{6-11a}$$

$$\mu\ddot{y} = \varepsilon E, \text{ where } E = \frac{V_d}{d} \qquad \text{6-11b}$$

it follows that

$$\dot{z} = const = v_0 \cdot \cos\alpha$$

hence:

$$z = v_0 \cdot t \cdot \cos\alpha \qquad 6\text{-}12$$

Integrating 6-11b once, and then replacing time (t) by distance z, as of equation 6-12:

$$\dot{y}_\ell - \dot{y}_0 = \frac{\varepsilon}{\mu} \cdot \frac{V_d}{v_0 \cdot \cos\alpha} \cdot \frac{\ell}{d} \qquad 6\text{-}13$$

Introducing the anode voltage $V_a$:

$$\varepsilon V_a = \frac{1}{2} \mu v_0^2 \qquad 6\text{-}14$$

and combining 6-14 with 6-13 and 6-10, yields:

$$\Delta = \frac{1}{2} L \cdot \frac{\ell}{d} \cdot \frac{V_d}{V_a} \cdot \frac{1}{\cos^2\alpha}, \quad q.e.d. \qquad 6\text{-}7$$

6.4.1.1.2 Collimation by two blocks of field.

Figure 6-19 shows the basic arrangement of an auto-collimating tandem. A first set of plates (1) is used to deflect a beam by an angle $\alpha$ off axis. After reaching the desired amount of parallax (h), a second pair of deflectors (2) is used to collimate the offset beam, i.e. to re-direct it parallel to axis.

Practical considerations make it desirable to operate both sections of the tandem from a common voltage ($V_d$). However, from equation 6-7, it may appear, that this is impossible, since the deflection-factor of the second section increases with elevation as $1/\cos^2\alpha$ . Fortunately, this influence is just balanced by an increment in beam velocity, occurring in the first section. After electrostatic deflection by $\alpha^\circ$ in the first Deflectron, the beam has acquired a transversal velocity component of:

$$V_T = V_0 \cdot \tan\alpha \qquad \text{6-15}$$

This raises the total beam velocity to:

$$V^2 = V_0^2 + V_T^2 = \frac{V_0^2}{\cos^2\alpha} \qquad \text{6-16}$$

Hence, the equivalent electron-volts of the beam entering the second Deflectron have increased from $V_a$ to $V_a/\cos^2\alpha$ . Inserting this value, instead of $V_a$ itself, into equation 6-7, we get for the deflection $\Delta_2$ from the second yoke alone:

$$\Delta_2 = \frac{L}{2} \cdot \frac{l_2}{d_2} \cdot \frac{V_d}{V_a} \qquad \text{6-17}$$

After this second deflection, the intermediate beam acceleration to

$V_a/\cos^2$ is cancelled by deceleration, and the beam-output voltage is back to $V_a$.

The deflection $\Delta_1$, produced, at the matrix M by the first yoke along, would have been:

$$\Delta_1 = \frac{L+s}{2} \cdot \frac{l_1}{d_1} \cdot \frac{V_d}{V_a} \qquad 6\text{-}18$$

Inspection of Figure 6-19 shows, that the beam leaves the second yoke parallel to axis, if:

$$\frac{\Delta_2}{\Delta_1} = \frac{L}{L+s} \qquad 6\text{-}19$$

Division of 6-18 into 6-17 shows, that this condition is met, provided that:

$$\frac{l_1}{d_1} = \frac{l_2}{d_2} = \frac{l}{d} \qquad 6\text{-}20$$

Hence, we can get collimation on a common signal voltage $V_d$, if the two yokes are "matched" (equal deflection factors). The resulting parallax then is:

$$h = \Delta_1 - \Delta_2 = \frac{s}{2} \cdot \frac{V_d}{V_a} \cdot \frac{l}{d} \qquad 6\text{-}21$$

where s is the separation between center-planes of the two yokes. Equation 6-21 indicates perfect linearity of position with signal voltage on the surface of a plane matrix, without restriction to small angles.

6.4.1.1.3 Complete selector unit: four blocks of field

Figure 6-20 shows a complete electrostatic character-selector comprising four blocks of field A B C D and a matrix M. The blocks A and D deflect upward by an angle $\alpha$, and the blocks B and C deflect downward by an angle $\beta$. If all four deflection-factors are ideally matched, the beam leaves the system on axis, after reading a selected character with parallax h. (solid line). In practice, a slight mismatch - within 2% - between deflection factors has to be reckoned with. Such mismatch is most apt to be of the type $A \neq B$, $C \neq D$, rather than $A \neq D$, $B \neq C$ since the yokes A and D, as well as B and C, are identical by design. It is important, therefore, to study the condition of the system in the presence of the above mis-match, as indicated by the dotted lines in Figure 6-20. Here, the deflection angles $\alpha$ are different from $\beta$.

Figure 6-21 shows the selector unit replaced by its 4 principal planes, and explains the symbols used below for the elongations $h_3$, $h_4$ and $h_x$. If $K_1$ and $K_2$ are $\ell/d$ ratios (deflection-factors) of the Deflectrons in group AD and group BC, respectively, the elongations h of the ray (1) through (4) can be readily expressed by use of equation 6-7*

* For max sweep angles of $2\alpha = 16^{\circ}$ as used in the "Printoscope" the factor $1/\cos^2\alpha = 1.02$ has been omitted from 6-22, causing less than 2% error.

above:

$$h_3 = \frac{V_d}{V_a}\left[\frac{p_1+q}{2}\cdot K_1 - \frac{q}{2}K_2\right]$$

$$h_4 = \frac{V_d}{V_a}\left[\frac{p_1+q+p_2}{2}\cdot K_1 - \frac{q+p_2}{2}\cdot K_2 - \frac{p_2}{2}\cdot K_2\right]$$

$$h_x = \frac{V_d}{V_a}\cdot\frac{x}{2}\cdot K_1$$

$$\frac{h_x - h_4}{S} = \frac{h_3 - h_4}{p_2} \qquad 6\text{-}22$$

From these 4 equations, it is possible to find the coordinate S of the virtual origin (O) of the exit ray #4 as follows:

$$S = \left(p_2 + \frac{1}{2}q\right) + \frac{p_1 - p_2}{2}\cdot\frac{1}{1 - \frac{K_2}{K_1}} \qquad 6\text{-}23$$

This expression does no longer contain the factor $V_d/V_a$. Hence, it is seen, that;

A - the system has a fixed optical center (O) whose position does not change in the process of character selection.

B - if the separation between principal planes is the same for both tandems ($p_1 = p_2$), the optical center (O) coincides with the mid-point on the system-axis. ($S = p+1/2q$)

C - if condition B is met, an accidental mismatch between Tandem-sections cannot dislodge the optical center from the point of symmetry. This condition is illustrated in Figure 6-20 for various degrees of mismatch.

Figure 6-20 shows ray tracings in 4 cases of sensitivity unbalance BC/AD, ranging from 0.5 through 1.0 to 1.25. It is seen, that a yoke mismatch results in an off-axis direction of the outgoing rays, but they still go through the same optical center O.

This optical center does not move, if the selector is in operation. Hence if an image forming lens ($L_2$) is provided between selector and screen, the image can be arrested by focussing the optical center (O) on the screen S. This image-arresting condition is desirable in view of securing straight base lines in multi-letter displays.

The above analysis has had two important consequences for the practical design of a "Printoscope":

a) It prompted the development of twin-Deflectrons, printed on a common glass body. (so-called "Tandem-Deflectrons").

b) It pointed out, that one can design for coincidence of image-arresting and optimum focus, by placing the character-matrix exactly midway between two of these Tandem-Deflectrons (mirror-symmetry)

6.4.2 Tandem-Deflectron Unit

Figure 6-22 shows an auto-collimating Tandem Deflectron unit, developed especially for use in the "Printoscope". This unit is the electrical analog of an optical double-prism: two prisms with equal and opposite refraction, free to rotate around a common axis.

Figure 6-23 shows the glass body and the film master used for photo-engraving. This unit is designated as type CA-2480, to indicate the respective angle-apertures for each section.

The 9-terminal glass-cone of each Tandem-Deflectron (apex angle 11.5 degrees, length 2-3/4 inches) carries two pre-aligned yoke sections (1), (2), separated by a shield (3). (Fig. 6-22) The latter serves as protection against wall charges and cuts down on fringe-field interaction. The length of the large Deflectron section is adjusted such, that it just collimates the sweep from the small section on a common voltage.

The deflection factors of these two printed Deflectron patterns are made equal within 2 percent. Hence, if the same voltage is applied to units (1) and (2) in opposing directions, the second Deflectron acts as a collimator for the first, and the beam leaves the Tandem parallel to axis, but offset by a controlled amount. The unit can produce $\pm 1/4$ inch of parallax with $\pm 160$ volt per terminal per Kilovolt per terminal. The two sets of electrical axes are coincident within $1/2^{\circ}$, and they are orthogonal within 15 minutes of an arc.

During the development of the Tandem Deflectron type CA-2480, the problem was encountered, how to evalutate experimentally the collimation-performance of the unit. Observations of parallax on very long beams are unattractive because of the strong influence of earth-field and other disturbances. Instead, we used a method of sweep-cancellation in a short tube, as shown in Figure 6-24.

The Tandem-unit is connected to a balanced source of 60-cycle voltage. The first section of the Tandem gets a fraction $V_1$ of this voltage, while the second section gets an adjustable, and opposite, fraction - $V_2$.

When the double-pot $V_2$ is operated, one observes a shrinkage of deflection on the screen S, L" away. If the plane of deflection is the same in both units, the original deflection $\Delta$ as observed with $V_2 = 0$, can be cancelled by $V_2$, and the scan on S collapses into a spot. Using equation 6-7 for deflection on a flat, we then have the equations:

$$\Delta = \frac{1}{2} L \cdot K_1 \cdot \frac{V_1}{V_a} \qquad 6\text{-}24$$

$$\Delta = \frac{1}{2} (L - s) K_2 \cdot \frac{V_2}{V_a} \qquad 6\text{-}25$$

where $K_1$ and $K_2$ are the respective "deflection factors" $\ell/d$. By division, we get:

$$\frac{K_1}{K_2} = \frac{V_2}{V_1} \cdot \frac{L - s}{L} \qquad 6\text{-}26$$

If the Tandem sections are matched, ($k_1 = k_2$) there should be:

$$\frac{V_1}{V_2} = 1 - \frac{s}{L} \qquad 6\text{-}27$$

If a developmental unit does not meet this condition, the length of the weaker section is scaled-up until balance is achieved.

6.4.3 Gun Assembly and Alignment

Figure 6-25 is a blueprint, and Figure 6-26 is a photograph of the completed gun-assembly of the "Printscope". The system starts with a beam forming section (1) which produces a narrow ($1^o$) beam with a first crossover ahead of the matrix (2). The selector section consists of two Tandem-Deflectrons 3 and 4 aligned for coincidence of their electrical axis. Since both Tandems are identical and self-collimating, all 16 terminals can be inter-connected. The entire selector section is then operated from two balanced signal voltages supplied through 4 socket connections.

The barrels 5a/5b are part of the image-forming section, to be discussed later. Unit #6 is a wide-angle ($65^o$) Deflectron for "letter-adress", i.e. for positioning of the selected characters on the screen. The entire gun has 16 socket connections and is 16 inches long. The over-all length of a complete "Printoscope" with 19 inch screen is 33 inches. Figure 6-25 shows the entire tube including the screen section with the "Barrier-Mask" intensifier.

It is evident that manufacture of this complex tube poses some exacting problems of alignment, both electrical and mechanical. These were met by some unusual instrumentation, using both electronic and optical techniques.

#### 6.4.3.1 Electrical alignment

As shown on Figure 6-27, the "Printoscope" gun (1) is placed on two supports (2) and (3), with the gun-axis parallel to an optical bench (4). ( Height-gauge (5)) An 18 inch micalex rod (6), carrying two wires in opposite grooves, is then inserted through the entire tube, as far down as the gun-anode (#1). This "dipole-jig" (6) is connected to a resonant balun-unit (7) which in turn carries a transparent cross-hair system (8), oriented with the plane of the dipole. The dipole-jig picks up signals from any of the Deflectron units connected to a 3 megacycle-oscillator in unit (9). A high-gain null indicator will go through zero if the dipole is at right-angles to the electric field inside the yoke under test. With this method, it is possible to align all 3 Deflectrons with each other within fractions of one degree.

#### 6.4.3.2 Optical alignment

Now, parallel light from a Schmidt optical system (1) is projected along the outside of the tube. The light beams are made parallel to the tube axis by adjusting a point-light source in (11), until there is coincidence of the images, projected on the screen (13) from the first (8), and a second (12) set of crosshairs. (12) was made identical to (8) by contact, prior to use.

A third protractor (14) carries the matrix in alignment with its own set of crosshairs. If this set is now adjusted for optical coincidence with the two others, the matrix-unit can be spotwelded into place.

6.4.4. Image Forming Section

Figure 6-25 indicates a minimum object-distance from matrix to image-section of 3 inches.

The theory of image-arresting as outlined above, demands, that the main lens should be capable of focussing at least as far back as the matrix plane, if not beyond. Hence, we are faced with the problem of producing images of controlled magnification between fixed planes, and with a given minimum object distance.

Figure 6-28 illustrates this condition. A short uni-potential lens ("Einzel") lens was first tried. With barrel-diameters made as large as possible (1 1/4 inches) for reduced spherical aberrations, the length of this lens was less than 2 diameters. Figure 6-28a shows, that a lens of this kind acts as a simple "magnifier", giving inverted images. However, due to the rather long object distance, the size of these images was too small ($m = 5$ rather than $m = 8$).

It was possible to increase character size by connecting the drift space to a lower potential than the selector space. However, this approach was abandoned for reasons of tube-cost and circuit complexity.

A satisfactory solution was found by extending the barrel length of the "Einzel" lens to more than 4 lens-diameters. Figure 6-28b shows, that this permits a mode of operation, where the system breaks up into two equivalent positive lenses $O_1$ and $O_2$, each of them being an immersion lens. Between them at (X), a small, inverted image is formed. In this mode, the long uni-potential lens is the equivalent of a refractive telescope. It has been shown above, in Figure 6-17d that this "Electron-Telescope" is indeed capable of projecting erect; i.e. non-inverted images, but with a 2-inch barrel, these images were too large. In the final "Printoscope" gun, we have increased the total barrel-length from 2 inches to 3.5 inches. This resulted in a reduction of image-size to the values required by specifications (m = 8 to 1). Furthermore, in order to achieve greater flexibility of letter-size adjustment, the Telescope-barrel was subdivided into two isolated sections, each 1-5/8 inches long, and each was led out separately (Fig. 6-25). In this final form, it was found that the electrostatic Electron-Telescope permitted magnification control over a 2 to 1 range without undue defocusing, and with selector and drift space at a common potential. This feature, which is documented in Figure 6-31 may permit high-speed electronic switching from small to capital letters by a small (60 V) change of bias on the lens barrel, if the system is well centered mechanically.

6.4.5 Over-all Performance Test

A tube of type shown in Figure 6-26 was put to a read-out test at the rate of 2430 characters per second. For reasons of expedience, the matrix was read in its own sequence. This simplifies the signal generating equipment. Figure 6-29a and b shows the staircase waveforms used for line and field scan, respectively, as well as the gating pulses. The gate-width was 100 micro-seconds. The step amplitude was 45 volt per terminal, making for a total staircase-amplitude of 360 volt, or 16 percent of the beam voltage (2200 V).

The adress Deflectron ran on a similar signal. Offsetting a 1/8 inch character by 1/4 inch required 31 volts, or about 1-1/2% of the drift-space voltage.

Figure 6-30 shows the circuit-diagram of the read-out signal generator built for this test.

Figure 6-31 shows a photograph of the displays obtained with an early tube sample. All images measured 2 by 2 inches. As one can see on Figure 6-31 a through c, the mark-to-space ratio could be adjusted from about 0. 5 to 0. 25, depending on the bias supplied to the "Telescope"-barrels. (#5a-5b in Fig. 6-26).

Figure 6-32 shows another test of magnification control. Here, the letter size was varied from 1/4 inch to 1/8 inch, by changing bias on the electron-telescope.

Figure 6-33 serves to document the effectiveness of the Barrier Mask in providing protection against secondary images. These are clearly evidenced in Figure 6-33a, where the barrier bias (BMA in Fig. 6-25) was disabled. When restored, this bias of -200 volt between mask and collector grid was found to reject all "ghost"-images behind the desired characters. This experiment shows that the barrier-mask is as effective on a high-speed display as it was found to be in earlier tests using lower frequencies.

While the quality of these early displays is admittedly not perfect, there seem to be no major hurdles left in the way of further refinement. The photographs are offered as a proof for the feasibility of the system.

### 6.4.6 Further Developments of the "Printoscope"

#### 6.4.6.1 Dual purpose gun

The absence of magnetic components external to the neck makes it possible to combine, within the same tube, a "Printoscope" gun, as shown in Figure 6-26, side by side with a separate Radar-display gun, also using electrostatic deflection. This dual-gun assembly is shown in Figure 6-34. It fits into a common neck of 3-5/8 inches diameter. Mutual interaction is minimized by a shield (1) made of wire-cloth, and by end-caps (2) on each of the adress-Deflectrons. A dual-gun of this sort can accomplish the display of Radar-echoes complete with identifying information, all within a common envelope. The use of two separate guns permits simultaneous dual-display with relatively simple circuitry. The same purpose could also be achieved with the Printoscope gun alone, using time division. However, this would require more complex switching and gating circuits, and would entail a comparative loss of brightness.

#### 6.4.6.2 Permanent display and storage

Another development within reach of the present status is the addition of "memory" to the "Printoscope" as it stands. The Barrier-mask accelerator, as described is essentially a storage screen. As we use it, there is a uniform charge-distribution on an insulated, perforated surface. However, by applying the collector-anode to an external source for video signals, while writing with constant current, the charge-distribution on the barrier-layer can be reversibly controlled resulting in a charge image of the signal.[25] This can be used, as is well known,[21, 25] to achieve point-by-point control of the mask-transparency for electrons from a separate flood-beam cathode.

After expiration of the contract period - in fact, on April 19, 1957 - an experimental tube of this type was tested, successfully. Using constant current for writing, and variable-voltage on the collector grid ahead of the MgO barrier-mask, it was possible to retain the images of simple scanning patterns for an average of 5 sec after cutoff. Complete fade-out of the stored image occurred after 25 seconds. The short duration of this "memory" was clearly traced back to ion-discharge, due to imperfect vacuum in the demountable. This test is reported here only to show that the Barrier-mask intensifier as developed under contract, can be used without major changes to add storage to a display. This includes the use of "equilibrium-writing", i.e. the re-writing of an image by the same beam, without prior erasure of the earlier image.

CONCLUSIONS

65° sweep with Deflectrons is practical, with two reservations:

1. soft beams, approximately 3 KV
2. shielded post-acceleration

Our developmental tubes, using conventional guns - type 10 U by General Electric and type 5 T by RCA - readily achieved television resolution (spot size .050 inch; overall resolution: 310 lines). This was done with post-acceleration of 8 to 1 from a drift-voltage of 2.5 KV to an ultor voltage of 20 KV.

The barrier-mask with Mg-0 layer is satisfactory, electronically. However, in its present form, it is unsatisfactory mechanically. The adherence of the Mg-0 coating to the glass-base is poor. Damage may result from peel-off, when tubes are subjected to shock and vibrations.

The wide-angle Deflectrons (1 1/2 inches long) seem to be adequately corrected in matters of circularity and pin-cushion distortion. However, their voltage stability is marginal and there is more evidence of deflection-defocussing now, than there was in our earlier 2 inch Deflectrons for medium angle.

Both defects can be reduced, to some extent, by scaling-up the dimensions of both yoke and neck, (see under recommendations).

Deflection defocussing depended as usual on beam diameter in the yoke region. Little trouble was encountered, when limiting stops were used to keep the beam diameter below .050 inch. With wider beams, .100 inch and above, dynamic focus modulation was found to be helpful in our initial experiments. With refined circuits - specially adapted to the particular service considered - dynamic focussing is likely to pay even greater dividends in connection with e. s. wide-angle deflection.

Two composite tubes were investigated, using more than one Deflectron:

1. the dual-deflection tube
2. the "Printoscope"

Tube 1 has never been sealed-off, but was only tested in the demountable, not even employing the BMA-structure. It was established, however, that one can assemble two or more Deflectrons under common axis with great accuracy, ($\pm$ 1/4 degree). Our method of using an RF-dipole for alignment - "RF-jig" - has been generally reliable and accurate.

The "Printoscope" has been overall - tested in the demountable, including the BMA screen section. We believe that the electrostatic approach is here potentially competitive with existing methods. Because of the absence of external magnetic fixtures, there is a definite possibility of developing twin-gun systems housed in a common neck. These tubes would facilitate the simultaneous display of Radar and identifying information. In a separate test, the Barrier-mask has been proven out as a potential storage-screen for such displays.

Our developmental "Printoscopes" were generally satisfactory. Some of the remaining problems are:

1. low light output
2. crosstalk from downleads into gun
3. production-variations in electronic magnification

Because of #2, the practical use of fast size-control by the electrostatic telescope is questionable at this time, at least until a better barrel-centering technique is developed.

#2 can probably be corrected by shielding: and it would be much improved by separate lead-out through the neck, as required by contract specifications.

#3: As to improvements in light output, see section on "recommendations".

## RECOMMENDATIONS

### A. Deflectrons

#### 1. Oversized units

There seems to be promise in developing Deflectrons of increased size. An attractive electrode would measure 2 1/2 inches in length and exit diameter, and would fit into a 3 inch neck. The voltage sensitivity of this oversized Deflectron would be the same as now. For its production, existing master-films can be used, after scaling them up photographically.

The advantages of such large-size Deflectrons are:

1) Greater voltage stability

2) Less deflection defocussing

3) Larger beam power capability

Number 1 results from scaling up all insulating gaps. --Number 2 is anticipated by theory (par. 3.0). It also follows from the increase of yoke diameter around a given beam. Number 3 refers to the increase of permissible beam diameter for a given yoke-to-beam area ratio.

#### 2. Better Production Techniques

All contract work was done by photo-engraving precision glass cones through a master film. This technique is accurate, but time consuming and costly. Besides, the open glass surface between platings has given rise to spurious deflection errors (hysteresis effects).

After some discussion with engineers from Corning, it seems possible to simplify and cheapen Deflectron production considerably, by using a pressed-glass and metal-painting technique as follows:

1) The glass cone is made from two half-shells, as generated by a plane cut through the axis of symmetry.

2) Insulating grooves are embossed; i.e., depressed below the active metal surfaces by pressing the half-shells hot against a conical mandril with the proper profile.

3) After embossing, the halves are frit-sealed and their elevated inner surfaces are brush painted with "fire paint" (silver or platinum immersed in volatile oil).

4) After "firing" the resultant thin metal surface is built up by electroplating.

B. Barrier Mask

To obtain better mechanical adherence, other methods for production of metal-oxide films should be tried. Magnesium-oxide can be generated by anodic discharge in a low pressure oxygen atmosphere, using an evaporated Mg-film to start with.

Another possibility is the use of "anodized" aluminum ($Ae_2\ O_3$) for the Barrier mask.

Magnesium fluoride coatings may be successful, if evaporated on a heated mask surface to achieve better build-up in thickness. Masks of better resolution than used in our work are now available from Buckbee-Mears & Company, St. Paul, Minnesota. The same company makes masks from stainless steel, as well as scaled-down versions of high transmission masks with high resolution for small sized screens. (5 inch and 10 inch tubes)

C. Low Voltage Guns

Improved resolution has been achieved with low anode voltages in guns of modern design (See Par. 4.0). Such low-voltage guns are most suitable for use in deflectronized tubes, in order to counteract inherent resolution limitations. If better spot focus becomes available, the mechanical resolution of the mask has to be increased also. Otherwise, dot-breakup at the focus mask may prevent the overall improvement from becoming evident.

D. "Printoscope"

The light output from the "Printoscope" can be much improved - as preliminary tests have shown - if the conventional gun is replaced by a small (.040 inch) Pierce-cathode. The crossover from this gun is designed to lie ahead of the mask. The $L_1$ lens can then be abandoned, and the total length of the tube shortened by about one inch.

## IDENTIFICATION OF KEY PERSONNEL

Key personnel working on this project during the final period covered by this report are:

| Name | Title | Approximate Hours Worked |
|---|---|---|
| Dr. K. Schlesinger | Chief Research Engineer<br>Electron Tube Research Dept. | 220 |
| Mr. A. Hogg | Mechanical Engineer | 405 |
| Mr. B. Maggos | Chemical Engineer | 385 |
| Mr. G. Costello | Senior Laboratory Assistant | 400 |
| Mr. J. Bujalski | Junior Laboratory Assistant | 370 |