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FINAL REPORT

CATHODOCHROMIC STORAGE DEVICE

(3 APRIL 1968 THROUGH 2 APRIL 1969)

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ABSTRACT

A unique memory and display device has been developed by combining a fast phosphor layer with a cathodochromic layer in a cathode-ray tube. Images are stored as patterns of electron-beam induced optical density in the cathodochromic material. The stored information is recovered by exciting the backing, fast-phosphor layer with a constant current electron beam and detecting the emitted radiation which is modulated by absorption in the cathodochromic layer. The storage can be accomplished in one or more TV frames (1/30 sec each). More than 500 TV line resolution and close to 2:1 contrast ratio are possible. The information storage time in a dark environment is approximately 24 hours. A reconstituted (readout) electronic video signal can be generated continuously for times in excess of 10 minutes or periodically for several hours.

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I. INTRODUCTION

Most display systems do not have a memory capability; data are usually stored in a buffer memory which continually refreshes the display. This is a very inefficient arrangement; a buffer memory with a capacity of the order of one million bits is an expensive piece of equipment. A much better system would be one wherein the display has an intrinsic memory capability (or vice-versa). The object of the contract effort described in the main body of this report was the utilization of unique properties of recently developed RCA cathodochromic materials to create such a combined memory and display (or MAD) device.

It is well known that cathodochromic materials store and display information; images colored into cathodochromic materials persist for times ranging from minutes to many hours after storage. This in itself is useful. However, a true memory must have the capability to recall stored information in some useful signal form. Under the present contract fast phosphors and cathodochromic materials have been successfully combined in such a way that information stored in the cathodochromic is optically detected to generate an output electronic video signal. Thus, the "buffer memory-display" problem is solved and a device with very unique capabilities which might be exploited in numerous other applications is developed.

II. BASIC PRINCIPLES AND DESIGN GOALS

The cathodochromic storage device is a low-cost, large-capacity memory and display unit built around a cathode-ray tube (CRT) wherein a fast phosphor layer is combined with a cathodochromic material as shown schematically in Figure 1. The cathodochromic material has the property that it undergoes a color change when it is bombarded with electrons (or cathode rays); it is restored to its original color by exposure to photons (or light) of appropriate wavelength. Powders of sodalite:Cl cathodochromic material, for example, are normally white; under electron beam bombardment a red coloration corresponding to an induced absorption band at 5200 Å is generated (Figure 2). The induced optical density is proportional to the electron beam exposure, and the coloration persists after the electron beam is removed. Therefore, a CRT electron beam modulated by a video signal as it scans a normal TV raster, stores a colored image in the sodalite powder layer. Viewed in reflected light, the stored image is a highly visible display. The presence of a fast phosphor layer which emits at the wavelength of the induced cathodochromic absorption (Figure 2) makes it possible to recover the stored information in the form of reconstituted electronic video signal. A small constant current electron beam scans the storage raster and the phosphor layer emits uniformly; the radiation emitted at any given point on the screen is absorbed by the image in the cathodochromic layer in direct proportion to the local induced optical density.

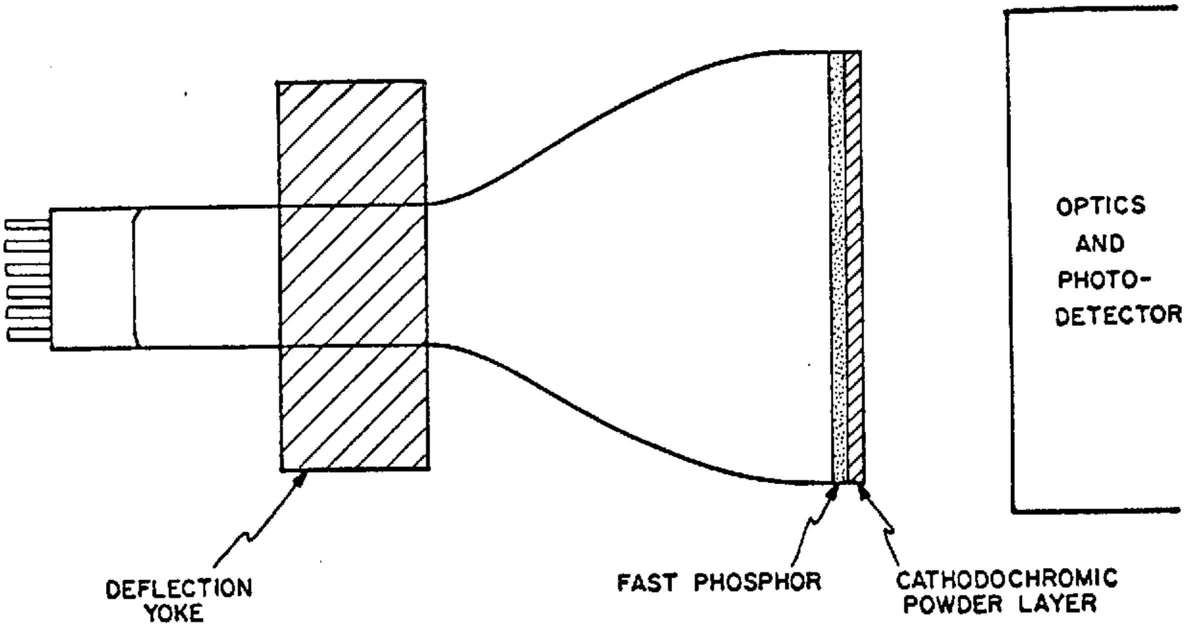

Figure 1. A schematic representation of the faceplate layers of a cathodochromic storage device tube; the readout detection system is shown schematically on the right.

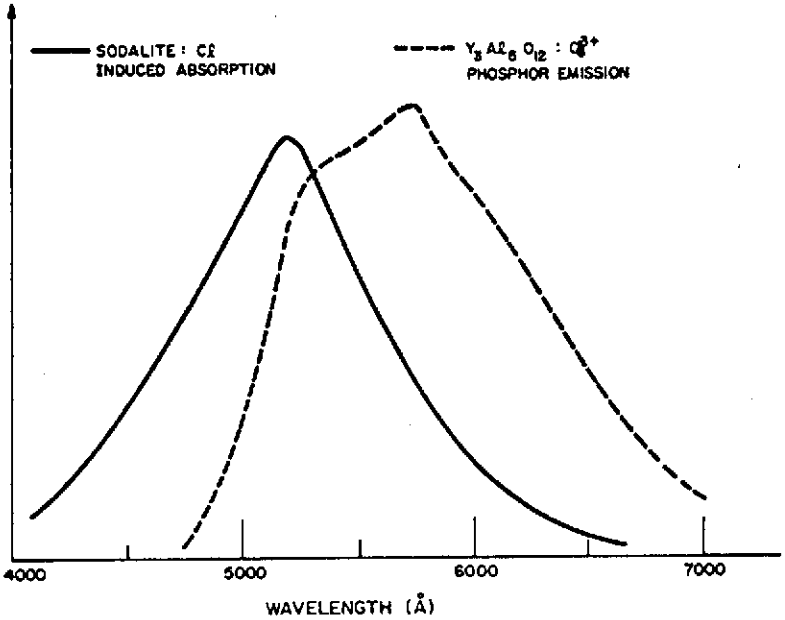

Figure 2. The electron-beam induced absorption spectrum of sodalite: Cl and the emission spectrum of $Y_3Al_5O_{12}:Ce^{3+}$ *fast phosphor.*

The phosphor emission, upon reaching an external photodetector (Figure 1), yields an electronic signal directly related to the video signal which modulated the electron beam during the earlier storage operation. The net result is a photoerasable display storage device with electronic readout capabilities, or in other words a photoerasable "memory and display" (MAD) device.

It is quite obvious that cathodochromic MAD CRT's might be used in many different ways. For example, computer-generated data might be stored for display and inspection; if further processing is deemed desirable the data might be read and returned to the computer. In this application binary storage with reliable recovery of each bit of stored information is essential. In another situation it might be necessary to receive telemetry data from a spaceship and in a single TV frame time, store it at a master console. The console operator would then inspect it and, if necessary, regenerate the information for distribution to remote display locations for use by other control personnel. In such telemetry situations, high speed storage and good gray-scale reproduction are essential. In computer-assisted design, coherent optical processing, and numerous other applications the prime characteristics or requirements might again be different. No single system could possibly be optimized for all of the possible applications of the capabilities inherent in the cathodochromic storage CRT. It is not surprising that the goals for this prototype contract effort are designed to give a broad demonstration of capabilities rather than a device optimized for a specific application.

Several specific design goals of the present effort are summarized below:

(i) Writing speeds sufficient for image storage in a single TV frame time (1/30 sec).
(ii) The ability to store 5 x 10^5 bits of information in a standard TV format.
(iii) The ability to photograph the stored information with a 35-mm camera, using an f/2 lens, ASA 64 film, and 1/30 second exposure.
(iv) A storage time of at least 15 minutes in a dark environment.
(v) The ability to perform external writing and selective external erasure functions.
(vi) A device not requiring controlled environments, external cooling devices, or input energy sources other than 115-V, 60-Hz ac power.
(vii) Minimum size and weight with the cathodochromic CRT itself being no larger than a standard 5-in. tube such as the RCA 5ZP16.

With the possible exception of item (ii) all of these goals have been met or surpassed. The methods and techniques employed and the final results achieved are described in the following sections of this report.

III. THE MAD CATHODOCHROMIC TUBES

The design goals and other pertinent factors impose several competing requirements on the bottle and gun assembly to be used in the cathodochromic storage device [see First Quarterly Report (1)]. The best available means of meeting these conflicting requirements is found in the gun and bottle of the RCA 5ZP16 flying-spot scanner tube. This is a 5-inch tube with electrostatic focussing, magnetic deflection, and a 40° deflection angle. It can safely operate at voltages up to 27 kV and beam currents up to 400 μA; at 400 μA the focussed beam spot diameter is approximately 140 μ. This is compatible with 500 x 500 line storage (2.5 x 10^5 bits) on a 3-inch x 4-inch raster where each bit has dimensions of 155 μ x 200 μ.

The materials chosen for the cathodochromic and phosphor layers were respectively sodalite:Cl and yttrium aluminum garnet doped with cerium. Sodalite:Cl is an aluminosilicate material having the composition $Na_8Al_6Si_6O_{24}Cl_2$. Appropriately prepared powders of this material are both photochromic and cathodochromic; the normally white powder develops an absorption band at 5200 Å (Figure 2) either when exposed to UV radiation in the 2500 to 3900 Å region or when exposed to high energy cathode rays (electrons). Cathodochromic coloration at 27 kV requires exposures of approximately 0.2 microcoulomb per cm^2, that is, an incident energy of approximately 5.4 mjoules/cm^2. The absorbed light energy required for optical erasure of stored images is approximately 10 times larger. Sodalite:Cl cathodochromic material was chosen for the cathodochromic storage device system because it yields the high visibility images required of a good display and, moreover, the induced absorption band is relatively sharp, thereby permitting the use of a ratio-recording technique discussed in Section IV of this report. [The experience gained in the present effort suggests that other more recently developed cathodochromic materials might offer some advantages in future MAD CRT's (Section 8).]

The phosphor in the cathodochromic storage device is required to have efficient emission overlapping the induced cathodochromic absorption band. Moreover, the phosphor emission decay time must be less than the time required for the scanning electron beam to travel from one stored bit of information to the next; at TV scan rates this implies an emission decay time of 0.1 sec or less. Early in the present effort we showed that yttrium aluminum garnet (YAG) doped with trivalent cerium ($Y_3Al_5O_{12}:Ce^{3+}$) is a phosphor which admirably fulfills these requirements. The emission spectrum of this phosphor is shown in Figure 2. Other YAG:Ce characteristics were described in the First Quarterly Report [1].

The design goals for the cathodochromic storage device placed difficult and somewhat incompatible requirements on the composition of the cathodochromic and phosphor layers. For example, fast (1/30 sec) writing on the cathodochromic layer implies that the backing phosphor layer should not appreciably attenuate the electron beam and, furthermore, the phosphor emission during writing should not appreciably bleach the cathodochromic. This would seem to indicate that the thickness (or screen weight) of the phosphor layer should be very small. However, the readout process requires an easily detected noise-free phosphor emission at excitation currents too small to significantly color the cathodochromic. The phosphor emission can only be noise-free if the phosphor thickness does not vary from point to point on the screen. Since the phosphor is in powder form this implies that one must use a relatively thick layer. A large, easily detected emission also argues for a thick phosphor layer. Obviously, the thickness of the phosphor layer cannot simultaneously fulfill all of these conflicting requirements, and some compromise thickness must be used. Similarly, the cathodochromic layer itself must be a compromise between a coarse high-contrast layer and a finer lower-contrast layer capable of high resolution. In all conflicts of this sort the optimum compromise solution is that which permits the closest approach to the design goals. The experiments performed in order to determine the cathodochromic storage tube parameters corresponding to optimum compromises were discussed in considerable detail in the Second Quarterly Report. We there concluded that optimum MAD tubes would result from the particle sizes, screen weights, and settling technique listed below:

Sodalite:Cl cathodochromic screen weight . . .	3 mg/cm^2
Sodalite:Cl cathodochromic particle size . . .	10 to 20 μ
YAG:Ce phosphor screen weight.	0.75 mg/cm^2
YAG:Ce phosphor particle size.	< 10 μ
Settling technique	high resolution

Tests on the resulting tubes have shown that these are indeed optimum parameter in light of the present design goals. (However, there is no significant degradation in performance when the high resolution settling technique is replaced with the simpler silicate-sulphate[2] settling procedure used in the fabrication of many other CRT faceplates.)

The electron beam exposure characteristics of the cathodochromic storage device tubes were measured, and typical results are shown in Figure 3. In part (a) of Figure 3 we plot white light contrast ratio as a function of exposure in microcoulombs/in^2. The contrast ratio is here defined as B_{us}/B_s where B_{us} and B_s are the measured reflected brightnesses of a typical faceplate area before and after switching by electron beam exposure, respectively. All brightness measurements were performed using a carefully stabilized illuminating lamp and a Spectra Brightness Spot Meter set on the foot-lambert scale (which is normalized to the photopic curve). Notice that an exposure of about 1.5 microcoulombs/in.^{2} leads to a white light contrast ratio of 1.2. This corresponds to exposing a 3-in. x 4-in. raster at 500 μA for 1 TV frame. In part (b) of Figure 3 the induced optical density defined as log $\frac{B_{us}}{B_s}$ is plotted against the logarithm of exposure. This particular plot of the cathodochromic excitation characteristic yields an approximate straight line with a slope of 0.12. The slope is a measure of the nonlinearity or "gamma" of the double-layer screen. For faithful gray-scale reproduction the overall gamma of any system must approximate unity. Since gamma here is approximately 1/8, accurate gray-scale reproduction will only be achieved if incoming video signals are processed through a compensating electronic nonlinearity or gamma corrector that follows the law

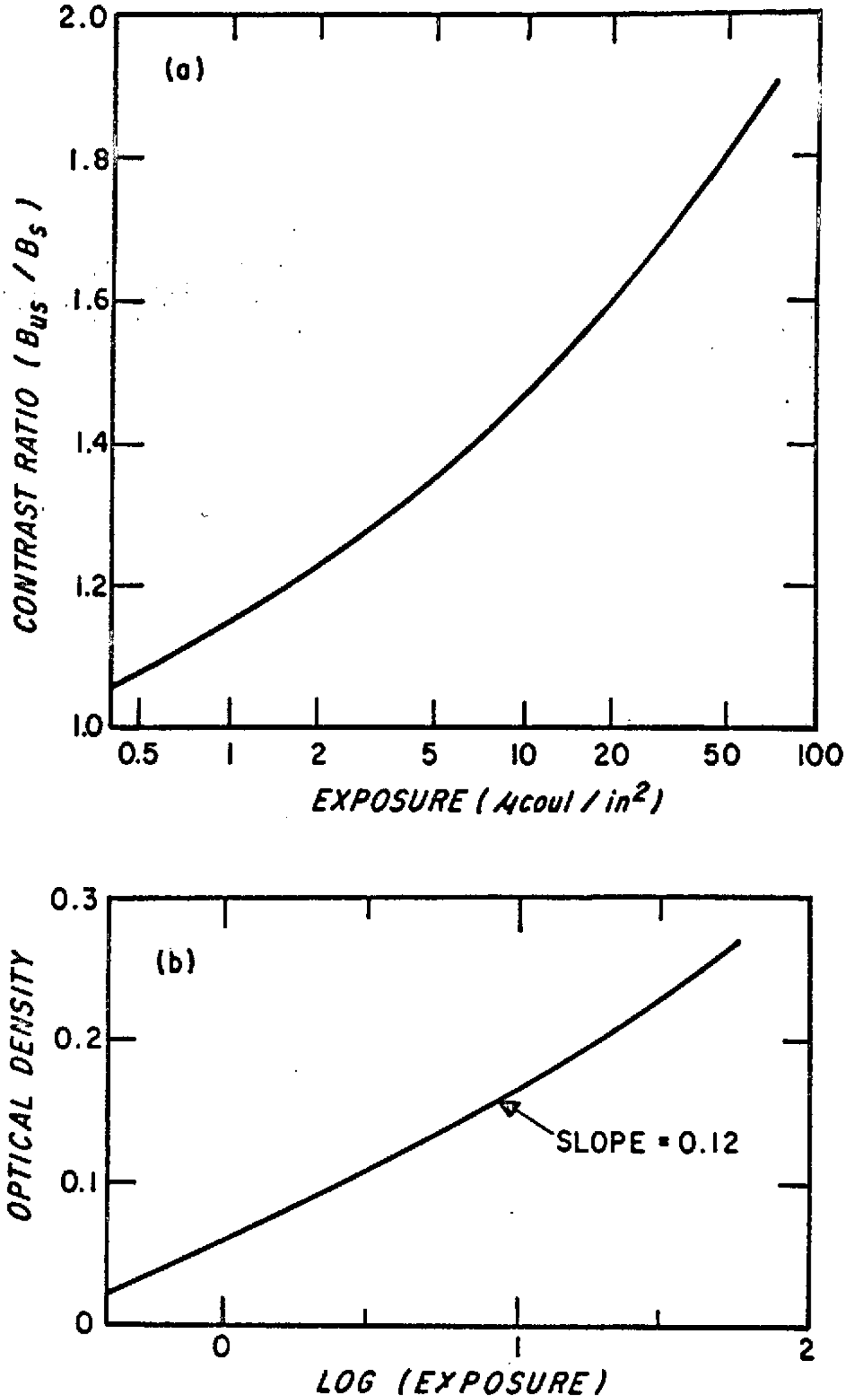

Figure 3. The excitation characteristic of combined sodalite: Cl cathodochromic material and YAG:Ce phosphor. Curve (a) shows contrast ratio vs. exposure on a logarithmic scale while (b) shows optical density vs. log (exposure).

$$E_{out} = (E_{in})^{8.0} \qquad (1)$$

This facility has been incorporated into the storage system using methods described in Section V.

It is evident from Figure 3(a) that these cathodochromic memory and display tubes are capable of white light contrast ratios approaching 2:1. This is quite adequate for a very good display as shown in Figure 4, a photograph of an image stored in the cathocochromic layer of one MAD CRT. The stored image is the negative of the incoming video signal because the cathodochromic is darkened in proportion to the incident electron beam exposure. Better than 400 TV line resolution is evident in this particular photograph, and the four gray levels of this particular test pattern are distinctly visible. In tests with other test patterns, full eight gray levels have been successfully recorded (e.g., Figure 5 of Third Quarterly Report).

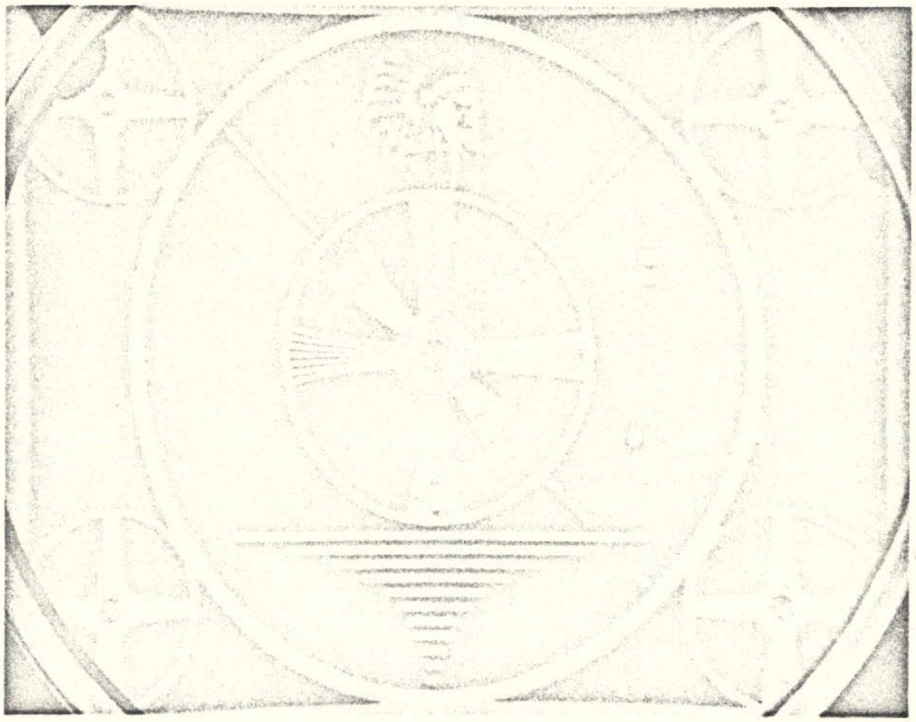

Figure 4. A "white light" photograph of a test pattern stored in the cathodochromic layer of a MAD CRT.

Further discussion of the performance of these tubes will appear in Section VI where we discuss the complete cathodochromic storage device system.

IV. THE OPTICAL SYSTEM

In a cathodochromic CRT, an electron beam modulated by a video signal stores images or information as patterns of induced optical density. The original video signal can only be recovered if one somehow scans the stored pattern and detects the induced optical density at each point on the CRT faceplate. The simplest approach is the optical flying spot scanner technique whereby a light beam of constant intensity is scanned over the stored image and the light intensity transmitted by each point in the image is detected. In the present cathodochromic storage device the scanning spot of light is generated when a fast phosphor layer behind the cathodochromic layer is excited by a constant current electron beam. It is then the function of the optical system to efficiently collect and detect the emerging phosphor emission and thereby regenerate the original video signal.

In the cathodochromic storage device several problems had to be considered as this simple optical detection technique was implemented. These arise primarily because the phosphor layer must be thin to allow fast writing (see Section III), and because long-term readout is possible only if the reading electron beam current is so small as not to appreciably degrade the stored image through cathodochromic coloration. Both of these factors limit the phosphor emission intensity available in readout, and the optical system must be highly sensitive and efficient; in other words, a sensitive detector must receive a large solid angle of radiation from each point on the tube faceplate. The small phosphor thickness introduces a further complication because a thin powder layer will necessarily show spatial nonuniformities which give rise to spurious modulation or readout noise. Furthermore, the optical system must be compact, it must allow visual observation of the CRT faceplate, and it must permit access to erase stored images.

The optical system, which was designed and developed based on these considerations and requirements, is shown in schematic cross section in Figure 5. As described in earlier reports, two detectors are used to eliminate phosphor noise through ratio-recording. The I_o detector receives only long wavelength (> 5900 Å) phosphor emission which is not modulated by the cathodochromic absorption; variations in the I_o output signal are entirely due to variation in phosphor emission. The I detector records shorter wavelength phosphor emission which contains not only the phosphor noise but also modulation due to the cathodochromic absorption. By taking the I/I_o ratio, the noise can, in principle, be eliminated and only the modulation signal of interest is retained. Efficient but compact light collection is accomplished through internally polished aluminum cones. The detectors are RCA 4465 photomultipliers with S-20 spectral response. B is a light-tight box which seals to a panel in the electronics rack; it excludes ambient light. The whole optical system is hinged so that it may swing about a vertical axis as shown by the photograph in Figure 6. This provides complete access to inspect or erase the cathodochromic faceplate.

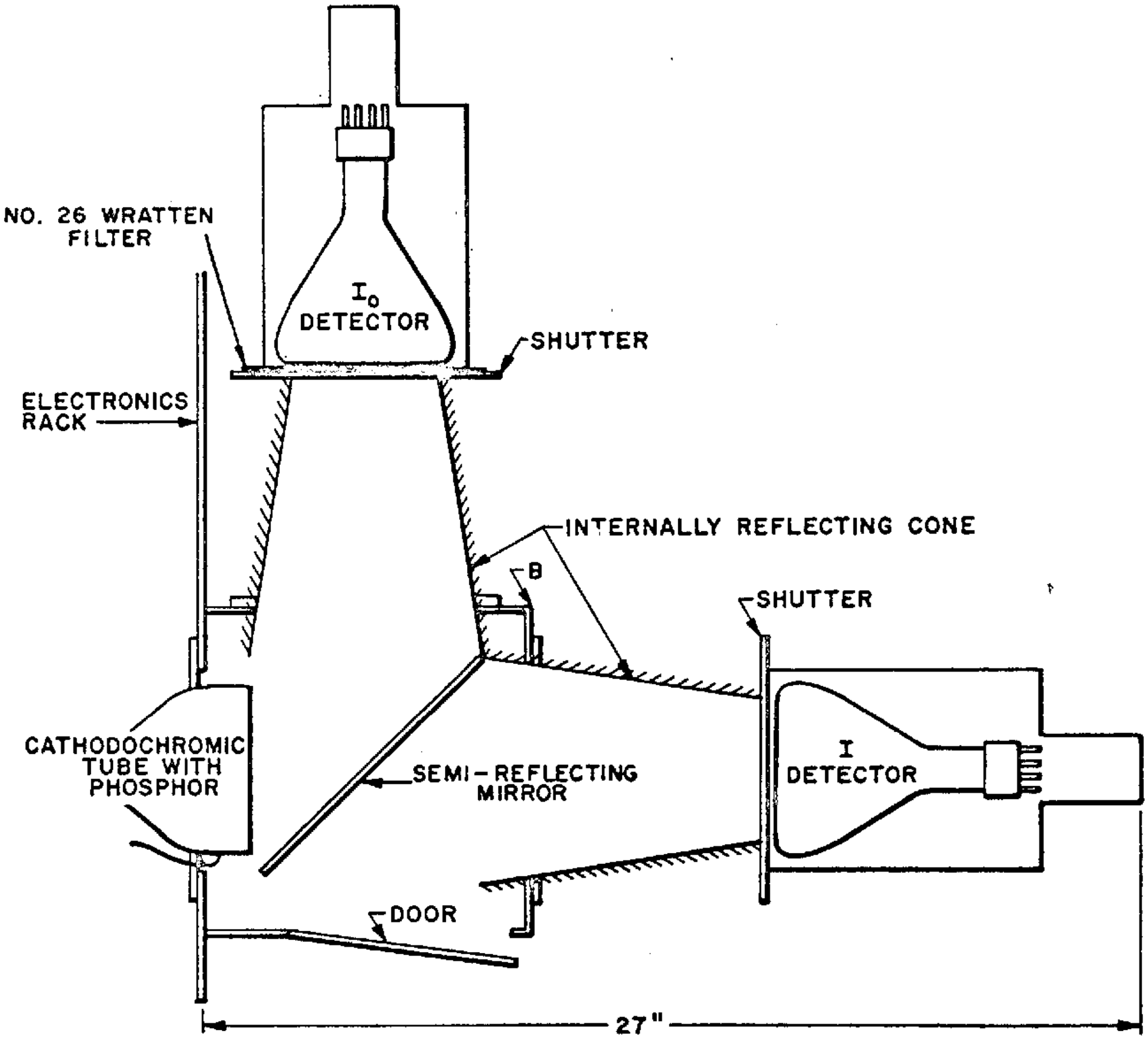

Figure 5. A schematic horizontal cross section of the optical system used to "read out" stored images.

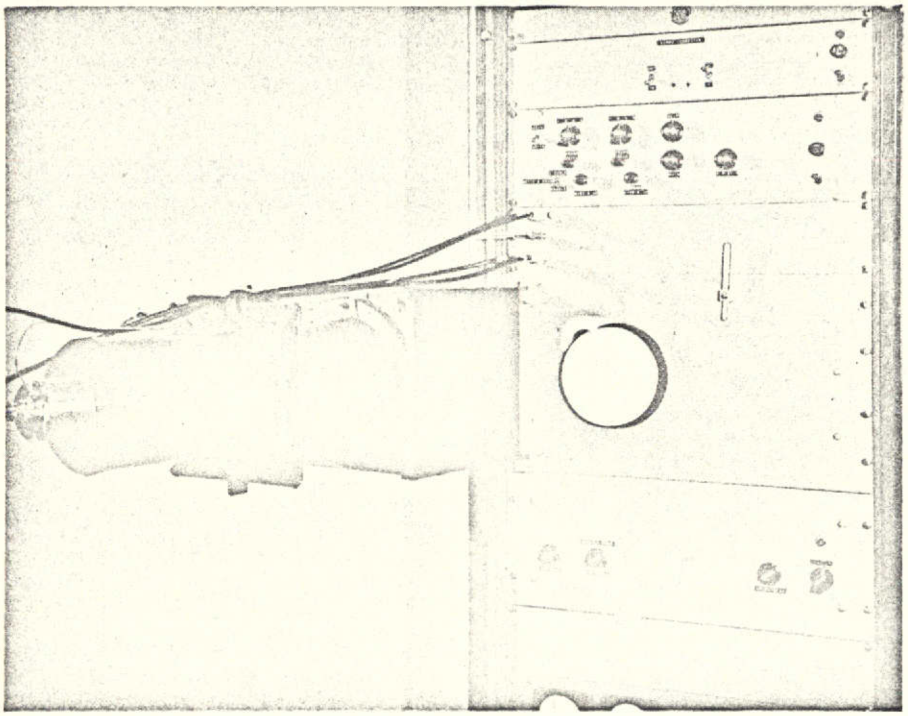

Figure 6. The optical system as it appears when it is swung open to expose the cathodochromic MAD CRT for inspection and erasure.

The hinged door shown in Figure 5 provides a more limited access to the faceplate; in most applications one can easily swing open the whole system and this door will not be extensively used. Whenever the optical system is opened, the shutters should be closed to protect the photomultipliers from room light or erasing light. If the system should accidentally be opened without closing the shutters a warning buzzer is automatically activated, and the power to the erase lamp is disconnected (Figure 25 of Appendix).

It should be noted that this is a relatively fast optical system. For a point at the center of the CRT all radiation within 26.5° of the forward direction is collected (neglecting reflection losses). Stated in other terms, an f/1 cone of radiation or all radiation within 0.21 π steradians is collected from this center point. For points near the edges of the CRT raster the light collection will be slightly less efficient.

In the prototype version of this optical system the beamsplitter was a dielectric dichroic mirror rather than a semi-reflecting aluminum mirror (see earlier reports). In principle, this was a very attractive approach because no other filters were needed and the maximum available phosphor emission was detected. In practice, the dichroic mirror led to shading problems in readout (see Third Quarterly Report) because the mean angle of incidence of the phosphor emission falling on the dichroic mirror varies with electron beam position along a horizontal scan line; the transmission characteristic of the dichroic mirror varies with this angle of incidence. Because no combination of filters was adequate to completely and efficiently overcome the shading problem, a semi-reflecting mirror in combination with the Wratten filter has been substituted for the dichroic mirror. This introduces some loss in efficiency but the overall sensitivity of the system is so great that continuous readout for times in excess of 15 minutes is still possible. The dichroic mirror approach to ratio-recording remains a valuable idea and it might be used to advantage if a part of the phosphor emission occurred at wavelengths well isolated from those wavelengths modulated by the cathodochromic absorption.

The optical system of the completed cathodochromic storage device incorporates, in addition to the components shown in Figure 5, an optical arrangement that makes it possible to produce a photographic record of information being written into the cathodochromic faceplate layer. This arrangement is most easily described by referring to the photographs shown in Figures 7(a) and 7(b). These pictures were taken with the hinged door (Figure 5) swung open. In Figure 7(a) we see, at the mouth of the I cone, a small plane mirror positioned so that light emitted by the phosphor layer and transmitted through the semi-reflecting mirror is reflected up to the lens of a camera mounted on top of the light-tight box. (An image of this mirror in the semi-reflecting beamsplitter appears in the center of the picture.) In this "photographing" position the mirror will appreciably impede the phosphor emission directed to the I detector. Therefore, in readout, the mirror is rotated by 90° as shown in Figure 7(b); only the narrow "edge-on" thickness of the mirror system then blocks radiation to the I detector.

The photography arrangement is such that a Nikon F camera with an f/1.4 or an f/2.0 lens plus a No. 2 closeup lens will properly and conveniently focus on the CRT faceplate. To focus one has only to loosen the wing nut which clamps the camera in position and then make the necessary adjustments while the camera lens remains seated in a light-tight felt-lined positioning socket on top of the mounting box. With the Nikon F lenses indicated above, a 3-in. x 4-in. raster on the CRT faceplate focusses to an image area of approximately 13 mm x 17 mm. In some situations it might be desirable to record somewhat larger images in which case we would recommend that a 55-mm f/3.5 micro Nikor lens should be used. The latter lens will obviate the necessity for the somewhat inconvenient closeup lens.

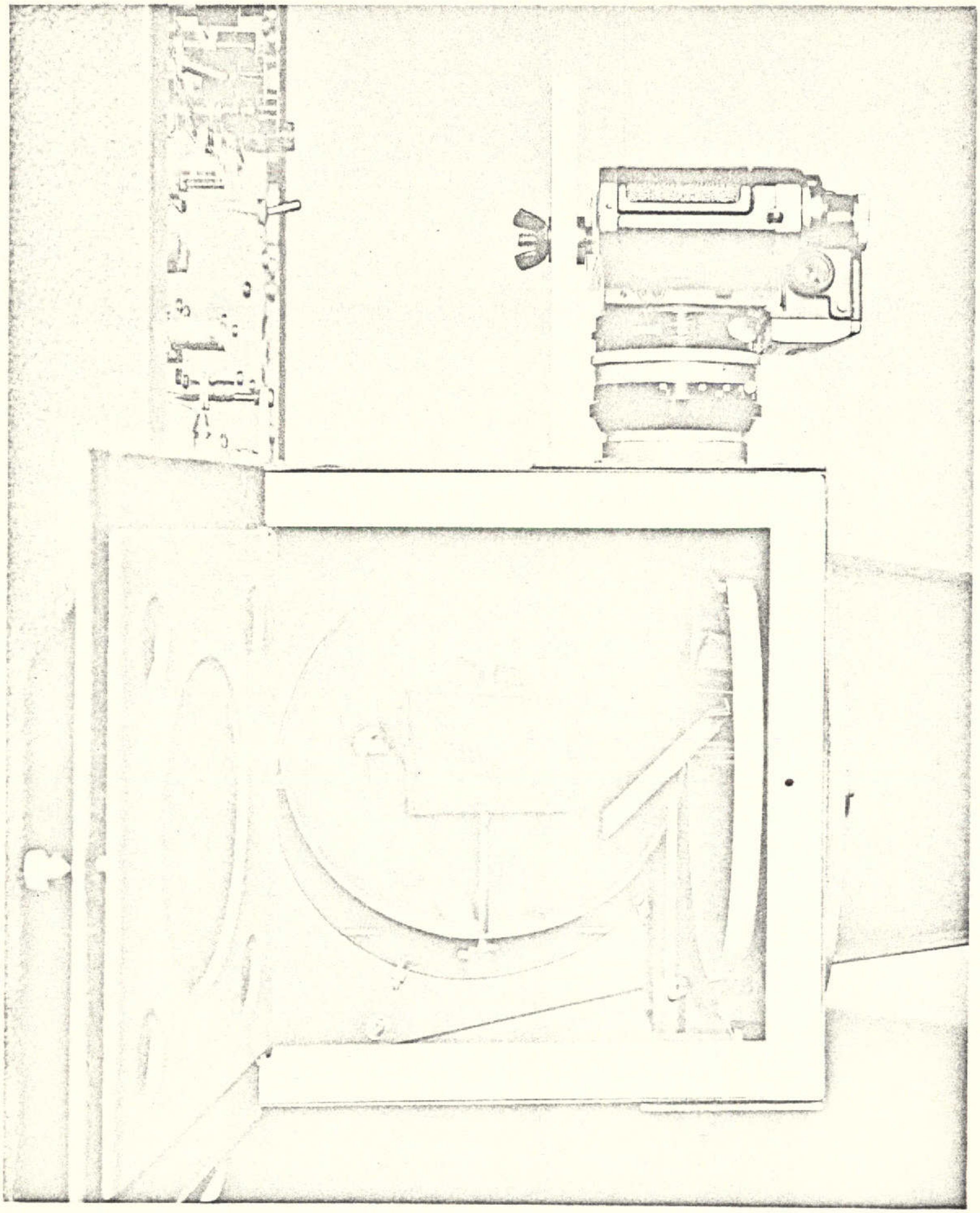

Figure 7 (a). The optical system used to produce a permanent photographic record of information being stored in the cathodochromic faceplate.

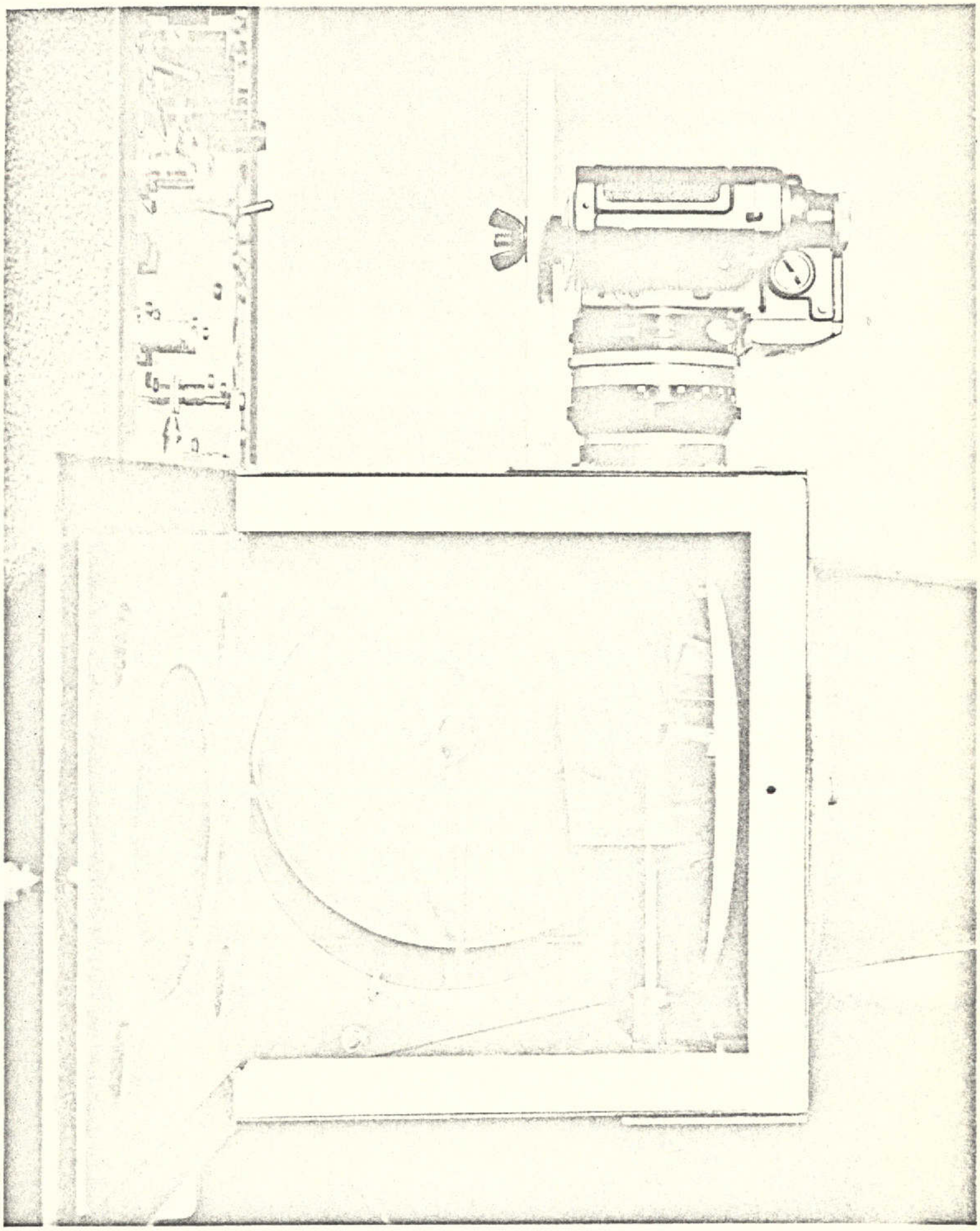

Figure 7 (b). The photograph system as it appears during image readout.

It should be noted that the photography system is designed to record the phosphor light which is emitted while a modulated electron beam is *storing* an image in the cathodochromic material. The photographed image is therefore a *positive* image of the incoming video picture whereas the picture actually stored in the cathodochromic layer is inverted, i.e., a negative image. The *negative* can be photographed using a long exposure during *readout* when the phosphor emission intensity is roughly a constant modulated by the cathodochromic absorption. In general, this is not recommended because the cathodochromic modulation is only about 50%, and high-contrast photographs will not be possible.

Further information on the performance of the optical system is presented in Section VI of this report.

V. THE ELECTRONICS SYSTEM

The electronic design in any system that can use standard interlaced television scanning is greatly facilitated by a vast quantity of prior art and immediately available equipment. As a consequence of this fortunate situation the circuit designer is relatively free to concentrate on those requirements which are unique to the problem at hand. The cathodochromic storage device was no exception. It was possible to utilize the basic scanning, synchronizing, and blanking circuitry from a commercially available precision television monitor. Nevertheless, the electronic design work was a very significant part of the present development effort. It was necessary to modify the video input circuitry of the monitor to adapt it to the specific requirements of the cathodochromic storage device. It was also necessary to design and develop extensive external circuits to perform counting, processing, and amplifying functions. We present here a relatively descriptive discussion of the electronic system with more specific information and detailed schematic diagrams being presented in the Operating Manual (see the Appendix). We begin with a consideration of the electronic system functions and requirements.

For convenience, flexibility, and compatibility with other equipment the cathodochromic storage device should operate from standard composite video signals (including standard synchronization and blanking pulses), and it should generate similar composite video signals during readout. Regardless of the input source, the stored signals should give high resolution images and faithful gray-scale reproduction. In Section III of this report we noted that there is a high degree of nonlinearity associated with the cathodochromic coloration process; the initial coloration takes place with much less energy than is needed to complete the process. To obtain accurate gray-scale reproduction, overall linearity must be restored to the system through compensating gamma corrector circuits which approximately satisfy the relationship.

$$E_{out} = \left(E_{in}\right)^{8.0} \tag{2}$$

It is important that images with high resolution be consistently stored and read out; this has implications on the electronics system design. High resolution is itself a somewhat ambiguous term; however, it is worth noting that a picture of true 500 x 500 line resolution contains 2.5×10^5 bits of information which must be received in a single TV frame of 1/30 sec. In standard TV systems the active time for each horizontal scan line is 52 μsec. The corresponding bandwidth required of the electronic circuitry is then $\frac{500}{2 \times 52 \times 10^{-6}} = 4.8 \times 10^6$ Hz. This significantly exceeds the bandwidth of a standard home television receiver.

One of the design goals for the present effort is a writing (or coloring) speed sufficient for image storage in a single TV frame (1/30 sec). This has several implications relative to the electronic system. The cathodochromic excitation characteristic presented in Section III of this report is such that single-frame writing at 26 kV requires electron beam currents of approximately 500 μA. This rather large current at high voltage must be accurately focussed to retain high resolution, and it must be operative for precisely one vertical TV frame. To produce higher contrast images it may frequently be desirable to write over a larger but accurately known number of frames; this implies the use of a "write timer" or "vertical frame counter".

During readout, further conditions must be satisfied. The phosphor layer must be excited by a low current electron beam which scans precisely the raster that was scanned during the storage operation; failure to maintain good raster registration will result in failure to detect all of the stored information. An upper limit on the readout electron beam current can easily be estimated by noting that one might commonly perform the storage operation in two frames or 1/15 sec at 500 μA. In readout the same accelerating voltage is used, and the electron beam uniformly and continuously colors the whole of the cathodochromic raster. When the readout beam exposure approaches equivalence with the storage exposure, the image in the cathodochromic will be very seriously degraded. Therefore, if we require continuous readout for 15 minutes the reading current must certainly be given by

$$i_{\text{readout}} < \frac{500}{15 \times 15 \times 60} \approx 0.04\ \mu\text{A} \qquad (3)$$

This is a very small current that should be held precisely constant because any fluctuations produce spurious and unnecessary noise in the phosphor emission level. In readout the capability to switch between single-frame, multiple-frame, and continuous readout is highly desirable.

The photomultiplier signals generated during readout must be amplified and processed to generate a composite video signal output which can then be used to drive a second cathodochromic dark-trace CRT, a standard kinescope, or some other suitable display device. In particular, one must include the circuitry necessary to perform the ratio detection operation discussed in the previous section of this report. Also, appropriate synchronization must be added to the processed photomultiplier output signals.

A block diagram of the interconnected units which perform the various functions and operations discussed above is shown in Figure 8. The incoming signal is fed directly to the gamma corrector. Only the video portion of the composite signal should be subject to gamma correction; the synchronizing (sync) and blanking information must not be modified or lost. Therefore, the gamma amplifier first separates out the sync and blanking signals and then applies gamma correction to the video portion of the signal. This is accomplished through field-effect transistors which exhibit

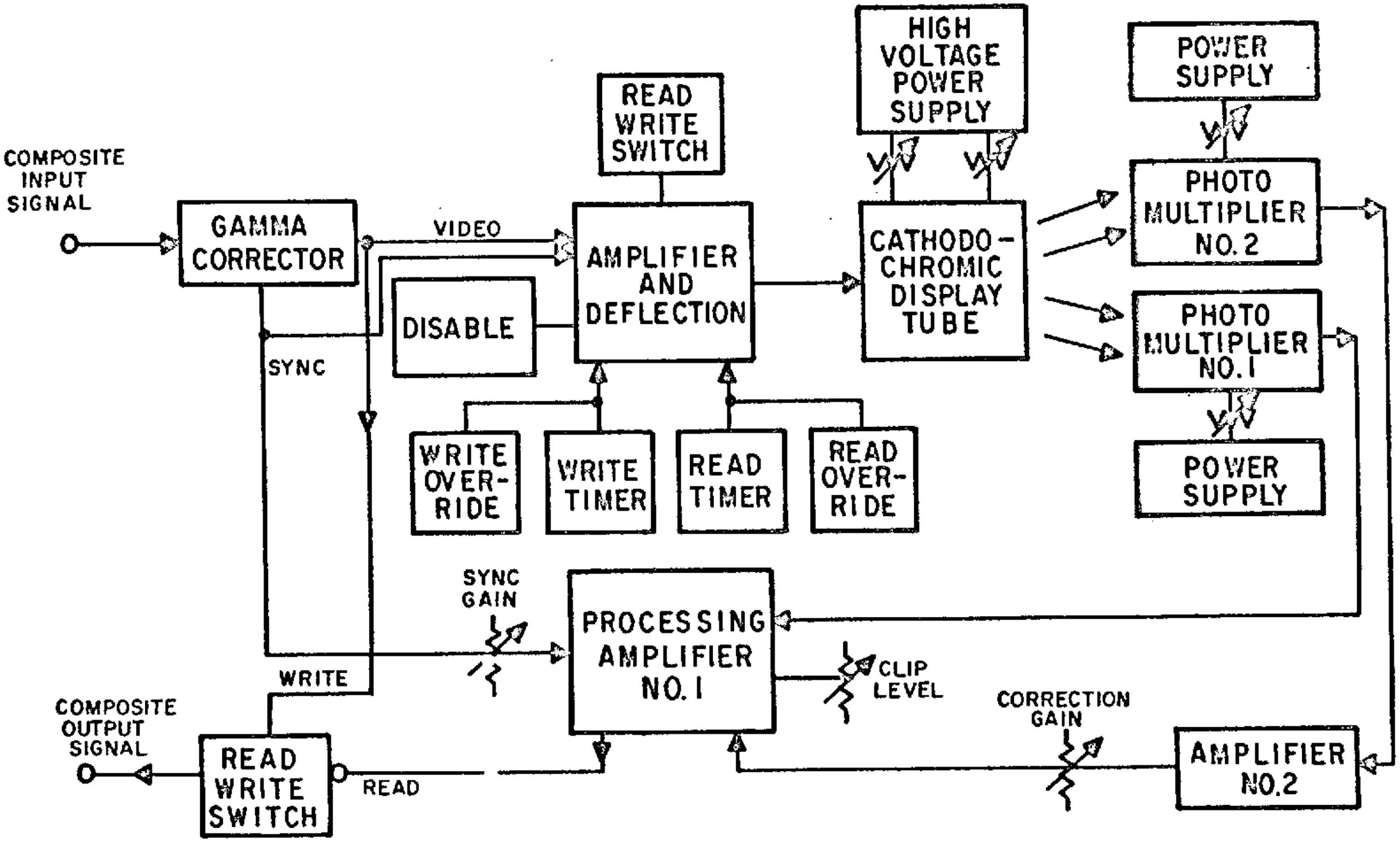

Figure 8. A schematic block diagram of the electronic system showing interconnections between the various functional ingredients of the system.

a quadratic relationship between drain current and gate voltage, i.e., $I_o = k(E_G)^2$. Two of these devices in a cascade configuration correct the signal so that the $E_{out} = (E_{in})^4$. A further quadratic correction is applied later through the CRT gun where beam current varies as the square of the drive voltage. The net result is then in accord with the requirements of Eq. (2), i.e., $E_{out} = (E_{in})^{8.0}$. The gamma corrector chassis is designed so that correction powers of 0, 2, and 4 can be selected by front panel switches. The largest value would normally be used with the presently available MAD cathodochromic tubes. After gamma correction, the video signal is recombined with the sync signal. A parallel but separate line supplies the same pulses to the deflection circuitry for scan synchronizing purposes and also to the processing amplifier where they are combined with the photomultiplier output signal. It should be noted that all sync information is derived from the input line; unless an input signal or some external sync source is operative a proper output signal cannot be generated.

The basic amplifier and deflection system is a somewhat modified Hewlett Packard Model 6946A precision television monitor. This particular monitor was chosen because it offers exceptional scan linearity and very stable deflection circuitry. The latter characteristic is essential to maintain raster registration during multiple frame storage and long-term readout. The monitor also permits extensive variation in the raster size; uses of this capability are discussed in the next section of the report. The frequency response of the monitor video circuits is flat to 8 MHz, thus allowing accurate storage of test patterns with greater than 500 line resolution.

The monitor has been modified to adapt it to the cathodochromic storage device system. The normal 17-in. kinescope has been removed and a separate mounting chassis for the 5-in. MAD cathodochromic tube has been installed. A separate chassis containing high-voltage, regulated power supply units for the 2nd anode (0-10 kV) and ultor (0-30 kV) electrodes of the 5-in. tube has been constructed. Other specific circuit changes and additions to the monitor are discussed in detail in the Appendix. Most of these changes are directly related to the various modes of operation of the system. For example, the READ-WRITE SWITCH on the master control panel activates or deactivates relays in the monitor and thereby transfers the monitor between WRITE and READ modes. In the WRITE mode an input video signal modulates the CRT electron beam; in the READ mode the beam current is held constant. Regardless of the position of the READ-WRITE switch a DISABLE-ENABLE switch respectively grounds or does not ground the CRT screen grid thereby prohibiting or permitting the flow or electron beam current. In the combined ENABLE and WRITE situation it is possible to write continuously by depressing a WRITE OVER-RIDE switch. Alternatively, the WRITE TIMER may be activated and the writing will proceed for a preselected number of vertical frames (1, 2, 4 or 8 -- see 2nd Quarterly Report). Similar options are available in the ENABLE and READ mode.

The optical output of the cathodochromic display tube is detected by (No. 1) and (No. 2) photomultipliers yielding I and I_o signals respectively (see Section IV). These photomultipliers operate from two separate power supplies; each is very well regulated and the voltage on each dynode chain is variable from 0 to 2 kV. (Operating voltages of 1 kV and 1.3 kV on the No. 1 and No. 2 detectors are recommended.)

The PROCESSING AMPLIFIER combines the amplified reference signal, I_o, and the noisy video signal, I, to produce the ratio I/I_o. The CORRECTION GAIN control adjusts the amplitude of I_o to the correct value relative to I. The dc signal level which results from a limited modulation by the cathodochromic absorption may be removed by adjusting the CLIP LEVEL. In the same amplifier, the sync signal is added to produce a composite video signal. The output signal can then be displayed on a simple external kinescope or other similar display devices.

VI. PERFORMANCE AND CHARACTERISTICS OF THE COMPLETED SYSTEM

The completed cathodochromic storage device system consists of the equipment shown in Figure 9 plus a separate TV picture monitor (RCA Model AL006W). The electronic system described in Section V is housed in the main body of the rack while the optical system discussed in Section IV is the unit mounted in front of the rack. The system is relatively compact; this prototype unit uses a 44-in. height in a standard 19-in. rack. The whole unit operates from a standard 115-V 60-Hz power line fused for 20 A. No cooling or ventilating devices are used and no unusual environmental controls are required.

A. STORAGE

Many of the system tests were performed using an "Indian Head" test pattern of the type shown in Figure 10. This photograph shows the incoming test pattern as it is displayed on the "picture monitor" TV set. The moiré structure in the photograph is a striking demonstration of the consequences of improper scan interlace. The "vertical hold" on the picture monitor should always be carefully adjusted so that such moiré effects do not appear. The high-quality precision television monitor (Section V) provides very accurate and reliable interlaced scanning; these moiré patterns are not observed in images stored in the cathodochromic tubes. (See, for example, the stored image photograph shown in Figure 4.)

Times as small as 1/30 sec are adequate to store useful images in the cathodochromic layer of a MAD CRT. Single-frame writing currents are typically 400 to 500 μA. When the system is properly adjusted, these 1/30-sec exposures yield images with a white-light contrast ratio of 1.2:1. In carefully filtered green light the single-frame contrast ratio approaches 1.4:1. With longer exposures, the MAD CRT's are capable of white-light contrast ratios approaching 2. With this range of contrast, eight distinguishable gray levels are readily displayed. The quality of stored images is somewhat improved when slightly less than peak writing currents are used because the beam spot size is then reduced leading to better resolution. Furthermore, the output voltage of the ultor power supply tends to sag slightly during the first field of very high current writing; when lower currents and longer times are used the raster size is somewhat more stable. Where it is convenient, multiple-frame writing at 50 to 150 μA beam currents is recommended.

The resolution of images stored in these MAD cathodochromic tubes is excellent. The available test pattern is completely reproduced with 500 TV line resolution; this corresponds to 1/4 million bits of stored information. It is believed that, at lower currents, the system is capable of storing more than twice this amount of information. This conclusion is derived from the known bandwidth of the storage circuitry (8 MHz), the characteristics of the 5Z electron gun (as discussed in the Second Quarterly Report) and the uniform, small-particle nature of the cathodochromic screens. Such very high resolution has not been demonstrated because no suitable input signal was readily available. Furthermore, as discussed below, such high-resolution patterns are

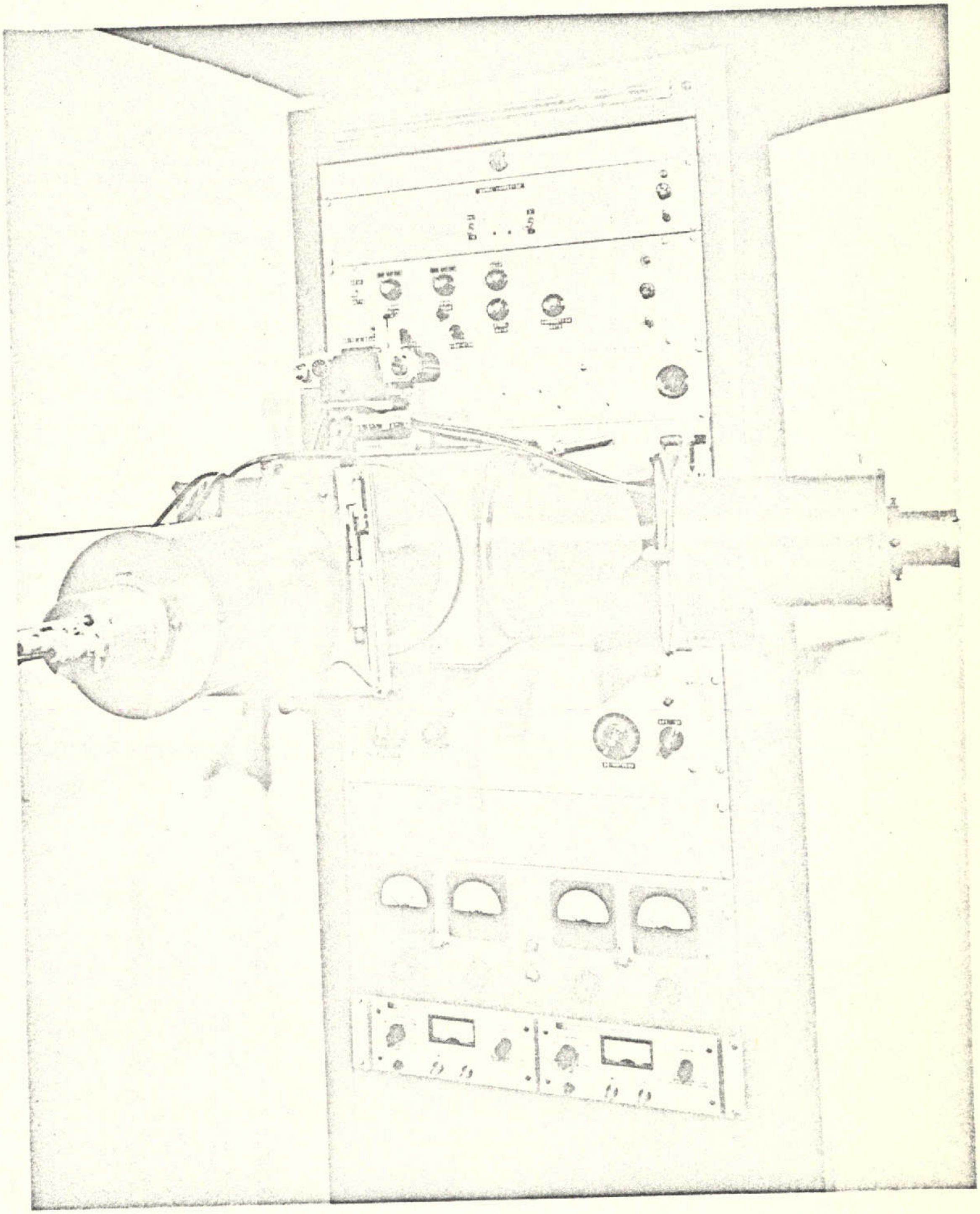

Figure 9. A photograph of the completed cathodochromic storage device system.

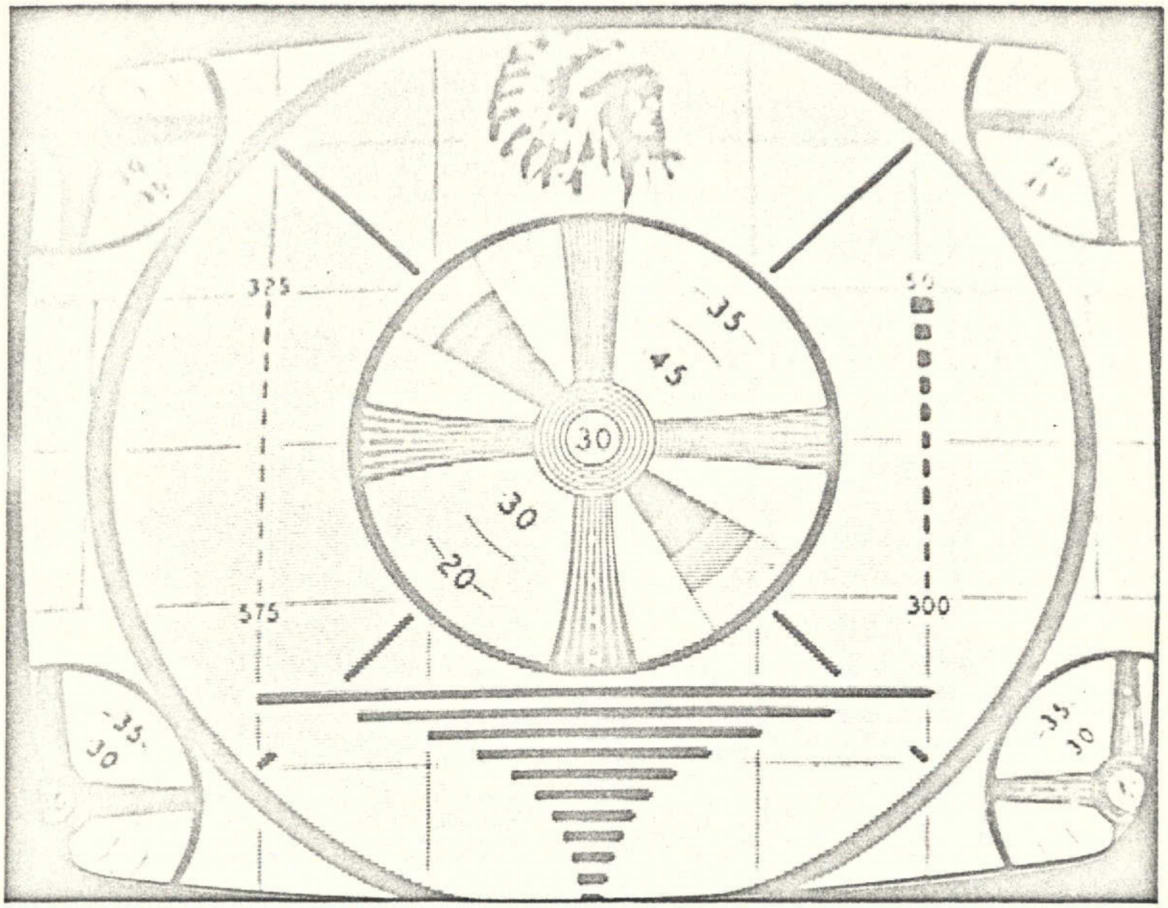

Figure 10. An "Indian Head" test pattern displayed on the portable TV "picture monitor".

not easily read out, and no simple standard monitor devices are able to display such high-resolution images.

The storage time of the cathodochromic device far exceeds the design goals of the present contract. Images stored in a dark environment and read out approximately 20 hours after storage are degraded by 3 dB relative to images read out immediately after storage. Exposed to the ambient radiation of typical room light (∿ 15 ft-lamberts) the equivalent degradation occurs in approximately 10 minutes.

The ability to obtain a permanent hard copy of information being stored in the MAD cathodochromic tube is demonstrated by the photograph in Figure 11. This is the image generated by the phosphor emission during single-frame writing (1/30 sec). It was recorded on ASA 64 film using the 50-mm, f/1.4 Nikon F lens stopped down to f/2.8. This surpasses the corresponding design goal. Furthermore, one would commonly use faster film and longer exposures so that much larger f/numbers would be appropriate. For reasons discussed in Section IV, we recommend that the 55-mm, f/3.5 micro Nikor lens be used rather than the 50-mm f/1.4 or f/2.0 lenses.

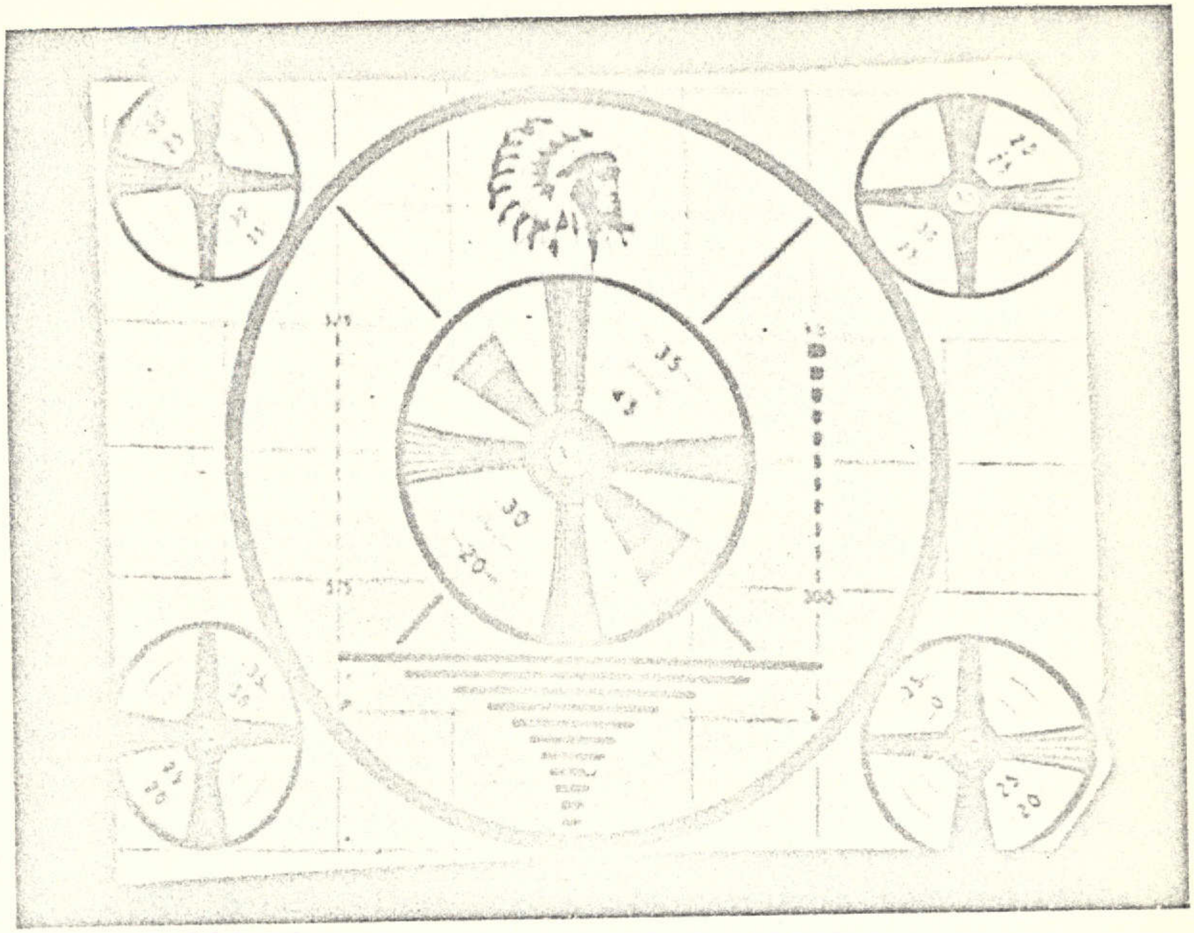

Figure 11. Single-frame photograph of incoming video data taken with ASA 64 film and an f/2.8 aperture.

B. READOUT

A typical photograph of the image appearing on the picture monitor TV set during readout of a stored test pattern is shown in Figure 12. Although this image is somewhat degraded by imperfect scan interlacing on the display monitor, it is apparent that the readout images do achieve typical commercial television resolution (i.e., 300 to 350 TV lines). This is supported by the fact that higher resolution images are observed when the same video signals are fed to a higher quality Conrac television monitor. However, even then, the resolution is somewhat inferior to the resolution of the actual stored images. This resolution degradation in readout is presently not well understood. Our tests suggest that it arises from scattering within and between the particles of the powder cathodochromic layer. In this case, the effect could be minimized through larger area tubes and thinner powder layers capable of higher cathodochromic optical densities. Better still, we hope that it will soon be possible to replace the powder layer with a thin cathodochromic film of uniform thickness.

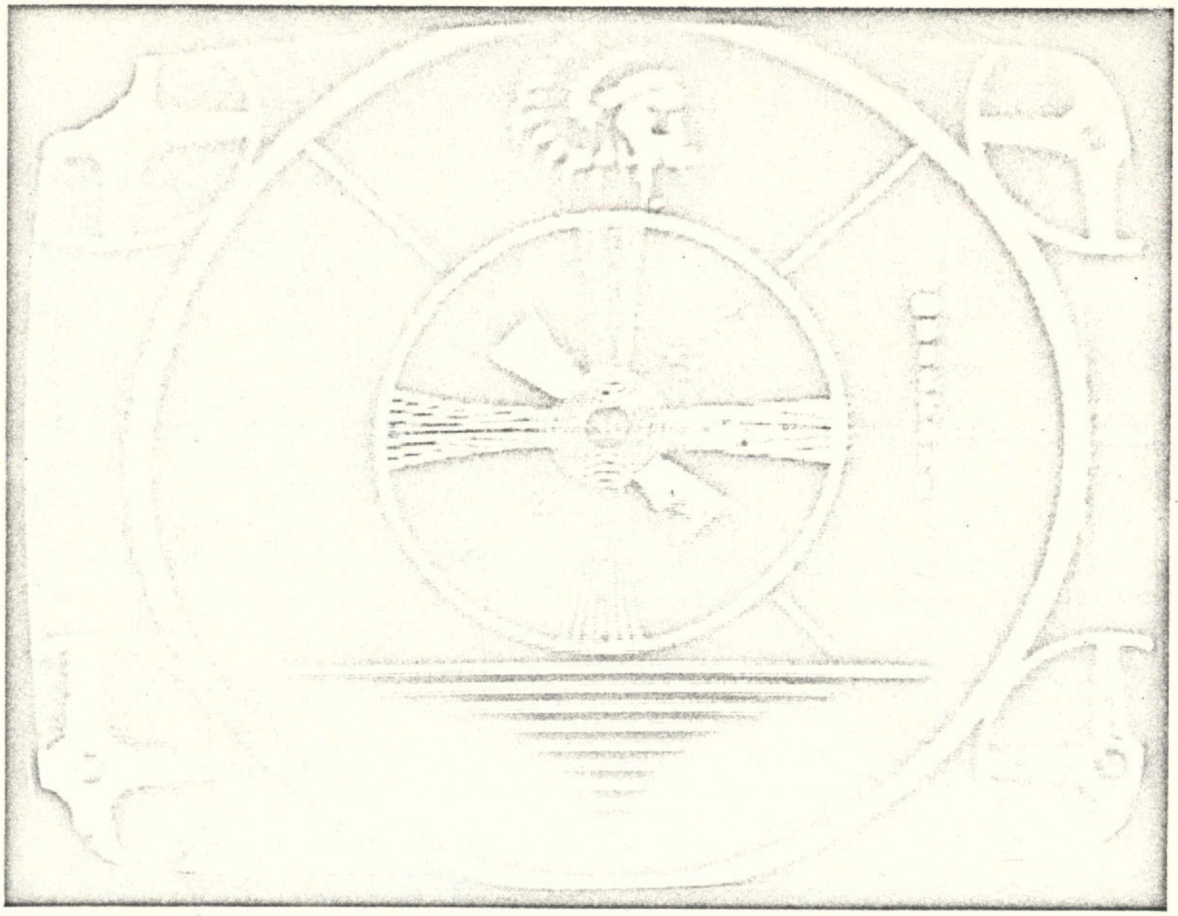

Figure 12. A photograph of the TV picture produced by readout of a stored test pattern.

The photograph in Figure 12 gives a slightly indirect indication of the system gray-scale capability. Four very-well-defined levels are shown; it is quite easy to see that separate and distinguishable levels could lie between each of these four.

The degradation of the stored image during readout is very slow. The scanning electron beam current during readout is typically 50 nA and continuous readout for 10 minutes degrades the output signal-to-noise ratio by less than 3 dB. Periodic readout over periods of several hours has been demonstrated. Even more extended readout periods can be achieved by manipulating the electron beam voltages as described and demonstrated below.

The penetration depth of an electron beam varies roughly as the square of the accelerating voltage. Therefore, with the layered structures of the MAD CRT, a low-voltage electron beam should dissipate most of its energy in the YAG phosphor layer. In this case, the electron beam will not appreciably darken the cathodochromic layer, and the readout process should proceed with very little degradation of a stored image. The flexibility of the precision television monitor made it possible to test this concept. A switch on the rear of the monitor allows selection of LARGE or SMALL raster scan where the two differ by 15 to 20% in linear dimensions. We proceeded to store an image using the LARGE raster. The direct image readout is shown as photograph (a) in Figure 13. The scan was then switched to SMALL and the ultor voltage reduced, thus allowing the raster to "bloom" until a readout image of the original size was produced. The second anode voltage was adjusted to optimum focus (at about 2.9 kV) and the readout image was photographed as shown in Figure 13(b). After 1 hour of continuous reading at this reduced voltage, the system still produced a high-quality readout image as shown in Figure 13(c).

C. ERASURE AND EXTERNAL OPTICAL WRITING

Until some better means is developed, it is recommended that a 600-W Sylvania "Sungun" be used for erasure. A bakelite shield which prevents bright reflected light from reaching the operator is found to be quite helpful. In addition, a filter containing a solution of potassium dichromate serves to minimize the radiant power falling on the tube; this avoids excessive heating of the tube faceplate. With this equipment complete erasure is normally achieved in 1 to 5 seconds. It should be noted, however, that excessive electron beam exposures as discussed in the appended operating manual will lead to permanent coloration or "burning" of the sodalite cathodochromic material.

Under the present contract external optical writing into the cathodochromic faceplate layer was demonstrated. Actually, the glass faceplate of the MAD CRT's is not very transparent at the UV wavelength required for true coloring of the sodalite:Cl. Therefore, the electron beam was used first to uniformly color the cathodochromic material, and the information to be stored was then optically written into the screen by preferential bleaching with longer wavelength light. In most cases contact printing of transparencies or masks was used (the extension to "light-pen" type of devices being obvious). The general image quality of optically stored information as detected using the YAG flying spot scanner is demonstrated in Figure 14, a photograph of the external picture monitor as it displays the MAD output from an optically stored image.

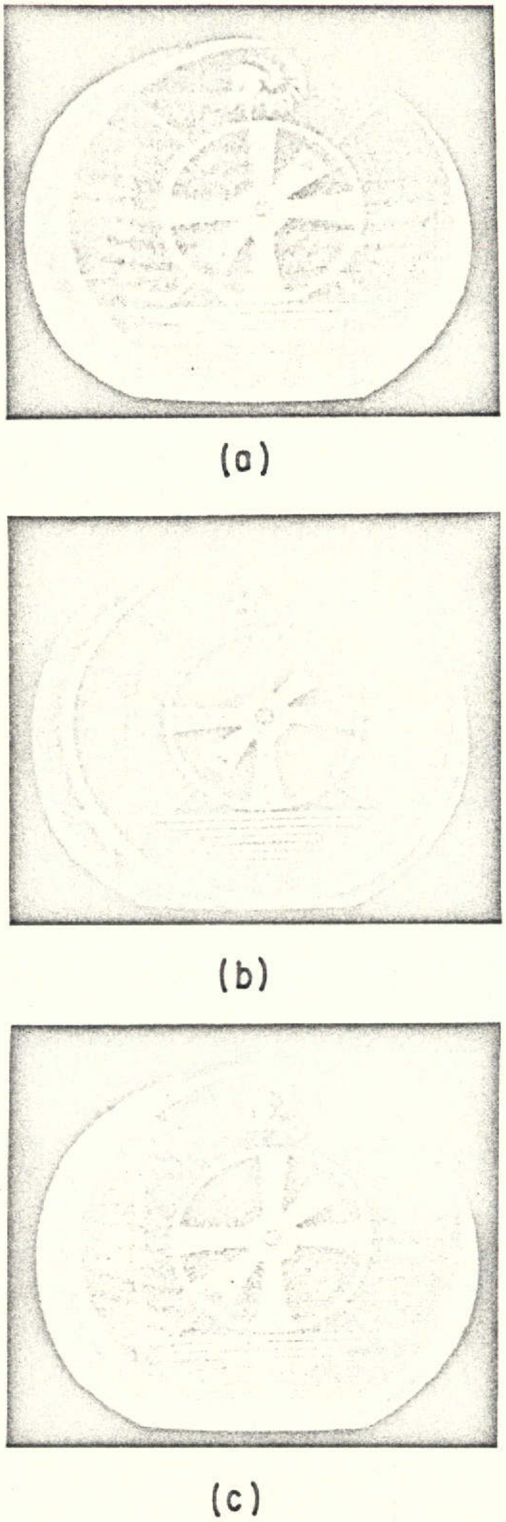

Figure 13. Photographs to demonstrate long-term image readout at reduced beam voltages (a) at 24-kV ultor voltage, (b) at 12-kV ultor voltage, and (c) at 12-kV ultor voltage after 1 hour of continuous reading.

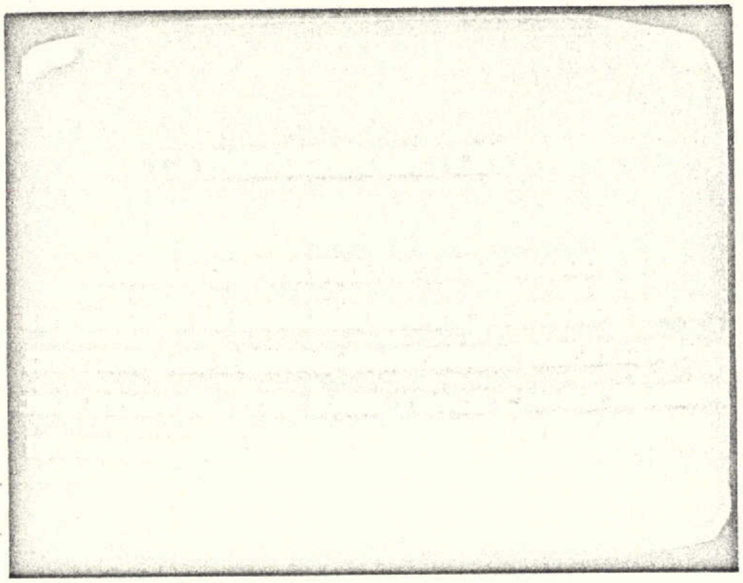

Figure 14. A photograph of a TV picture generated during electronic readout of an image stored optically in the cathodochromic layer of a MAD CRT.

VII. CONCLUSIONS

The cathodochromic storage device substantially meets all of the design goals of the present contract effort. Information, presented in a standard TV format, is stored in a single TV frame time. Images with better than 500 TV line resolution and close to 2:1 contrast ratio are recorded. The information storage time in a dark environment is approximately 24 hours. At any time, the stored information may be recovered in the form of a reconstituted electronic video signal. The reconstituted signal can be generated continuously for times in excess of 10 minutes. The resolution in readout is approximately 350 TV lines. This device should be very useful in a wide range of applications. We believe that further work will lead to cathodochromic storage devices capable of more efficient writing, higher contrast storage, and greater readout resolution.

VIII. RECOMMENDATIONS FOR FURTHER WORK

1. Flexible use of the cathodochromic storage device is somewhat impeded by the present method of optically erasing images. The face of the MAD CRT must be exposed to an unwieldy "Sungun" erasure lamp which tends to blind the operator. We believe that a much more desirable device would result if the MAD CRT were capable of internal erasure. We further believe that this might be done electronically and potentially selectively by combining the latest RCA cathodochromic materials with appropriate phosphors. Efforts to develop such an internal erase system should be pursued immediately.

2. The prototype optical detection system is somewhat large and clumsy. In situations where long-term readout is not required it should be possible to eliminate the photomultiplier detectors and complex optics in favor of a less sensitive but much smaller and more compact system. This possibility should be investigated.

3. For purposes of a very-high-quality display the MAD CRT's should be capable of contrast ratios of 5:1 or greater. To achieve this it is necessary to develop cathodochromic materials of greater optical density. It is desirable to develop simultaneously methods of screen preparation which might make better use of the optical density range presently available.

These three items each suggest a development program with well-defined and realistic goals. A concentrated program in any of these areas is likely to be successful; the results will be significant and worthwhile. We hope that such programs can be initiated in the near future.

IX. NEW TECHNOLOGY

A. TITLE: EXTERNAL OPTICAL WRITING

Page Reference: 26

Comments: External optical writing onto the cathodochromic faceplate layer with subsequent conversion of the written information into a TV signal format has been demonstrated.

B. TITLE: PROLONGED READOUT USING LOW VOLTAGE

Page Reference: 24

Comments: It has been shown that images stored in MAD CRT's can be continuously read for hours without image degradation by using low electron beam voltage during the readout operation.

APPENDIX

AN OPERATING MANUAL

This Appendix gives the instructions, directions, and precautions pertinent to operation of the prototype cathodochromic storage device described in this Final Report. It should be borne in mind that the present device is the product of a research and development effort performed in a research laboratory; it is the first cathodochromic storage device ever constructed. As a market item from a production facility the system would doubtlessly be modified, streamlined, and improved. RCA would welcome suggestions and information regarding changes and improvements which might be incorporated into future cathodochromic storage devices.

A. INSTALLATION

For purposes of shipping, the tubes, the detector system, and the monitor are all packaged separately from the electronic system. The first step after unpacking should be the installation of one of the three MAD tubes supplied. (These are labelled as 14-3, 39B and 15C; 14-3 and 39B are good MAD tubes, 14-3 being the better. Tube 15C should be used only for storage display). Largely because of a yoke rotator attachment installed following a NASA request during acceptance testing, this operation requires several steps. Performance of these steps in the order given below is recommended whenever a tube is installed or changed. In the initial installation it will be necessary first to remove the black bakelite box that excludes light from the main body of a mounted tube; this is accomplished by loosening the wing nut on the left rear corner of the box and then lifting the box back and up from the chassis. The deflection yoke assembly is contained in a box tied to the chasis in which the cathodochromic tubes are normally mounted.

1. From the front of the rack insert the base of the tube through the hole provided and through the deflection assembly. Leave the tube projecting about 2 in. through the chassis panel.

2. Seat the tube in the mounting brackets and insert the 0 to 30 kV power supply lead in the ultor cap near the face of the tube.

3. Shove the tube back on the mounts until the faceplate projects 7/8 in. beyond the front of the panel on the mounting chassis. This position should be maintained during all subsequent steps.

4. Move the yoke assembly back as far as possible and orient it so that the yoke cable is pointing toward the chassis.

5. Place the black bakelite box in position by lifting it in over the rear of the tube, setting it down over the tube, and then sliding it forward into the wing nut assembly that holds it in position. The front of the box should now be against the chassis panel.

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6. Check that the ultor and deflection leads come through the slots provided and tighten the wing nut.

7. Slip the "position-indicator" needle over the rear of the deflection yoke assembly. Point the indicator to the left and use the screw on the right to lock the needle to the yoke assembly (be careful that the screw seats in the indentation provided). Thread the yoke "positioning" screw into the threaded hole in the rear of the bakelite box.

8. Place the base socket on the MAD tube while firmly holding the tube in position by its own base.

To remove a tube these operations should be performed in reverse sequence. The deflection yoke may at any time be rotated by unscrewing the "positioning" screw and moving the position indicator needle to one of the other six possible orientations. Rotations in 36° or 90° steps are possible.

The optical system containing the photomultiplier detectors is now easily installed. Set this unit on the hinges at the left front corner of the electronics rack and connect the high voltage (HI.V.), emitter follower (E.F. VOLTS), and photomultiplier signal (P.M. SIGNAL) leads to receptacles on the "DETECTOR CONNECTION PANEL". The cables from the I_0 detector are marked with the letter B; they must be connected to the right-hand member of each pair of receptacles.

The cathodochromic storage device has been shipped with most of the cables already connected. To complete the assembly it is only necessary (i) to connect the PICTURE MONITOR TV set to the "VIDEO OUT" UHF connector on the rear of the PRECISION MONITOR (deflection chassis) and (ii) to supply a composite video input signal to the "VIDEO IN" jack on the rear of the GAMMA AMPLIFIER. The PICTURE MONITOR is an RCA Model AL006W portable TV set modified to accept a VIDEO feed through a BNC connector on the rear of the set. A rear-mounted toggle switch selects either the VIDEO input from the storage device system or a regular rf pickup mode for "off-the-air" TV programs.

B. FUNCTIONS OF THE CONTROLS AND SWITCHES

Starting at the top of the rack, the GAMMA AMPLIFIER carries three control switches:

ON-OFF: AC power line switch

IN-OUT: Determines whether gamma correction is applied to incoming signals; in the OUT position, no gamma correction is applied.

2-4 : Determines whether the applied gamma correction is 2 or 4; i.e., the value of X in $E_{out} = (E_{in})^X$ is 2 or 4.

The CONTROL PANEL governs the overall system operation through the following switches:

READ-WRITE: Selects the operating mode. In WRITE, a high current electron beam modulated by the video input signal stores an image in the cathodochromic MAD CRT. In READ, stored images are detected and displayed on the external monitor.

DISABLE-ENABLE: Prohibits or permits electron beam currents in the MAD CRT.

WRITE OVER-RIDE: Depress for continuous writing when in the WRITE and ENABLE mode.

FRAME-WRITE: In WRITE AND ENABLE, depressing and releasing this pushbutton switch causes electron beam writing for the number of TV frames (1, 2, 4 or 8) indicated by the adjacent frame selector switch.

READ OVER-RIDE: In READ and ENABLE depressing this pushbutton causes continuous image readout.

FRAME-READ: The analog of FRAME-WRITE.

CORRECTION GAIN: Controls the gain of the reference (I_o) photomultiplier signal.

SYNC-GAIN: Controls the amplitude of the sync signals in the system output video.

CLIP LEVEL: Adjusts the dc bias on the output video signal.

The PRECISION MONITOR has controls on both the front and rear of the chassis and many of these are either self-explanatory or covered in the manufacturer's manual delivered with the cathodochromic storage device.

BRIGHTNESS: Controls the magnitude of the writing electron beam current.

CONTRAST: Controls the modulation level of the writing electron beam current.

READOUT PHOS. EXC. LEVEL: Controls the magnitude of the constant phosphor exciting electron beam current during readout.

SCAN LARGE-SMALL: Selects rasters of relative sizes 1.0 and 0.8 respectively.

SYNC INT-EXT: Determines whether the monitor uses its own internal synchronization or external sync from the composite video input (EXT is normally used).

The high-voltage power supply has VOLTAGE and REGULATION controls for both the ultor (0 to 30 kV) and 2nd anode (0 to 10 kV) power sources. The REGULATION controls set the voltage levels at which the output currents are regulated. The photomultiplier power supply is a commercial unit described in a manual supplied with the equipment.

C. TURN-ON PROCEDURE

Turn ON the ac power line switches on the GAMMA AMPLIFIER, CONTROL PANEL and PRECISION MONITOR chasses. Put the DISABLE-ENABLE switch on DISABLE. Turn the VOLTAGE dials on the high-voltage power supply as far as possible counter-clockwise and turn on the ac power switch. Allow 1 min warmup time. Turn the two VOLTAGE controls simultaneously until the current meters indicate 0.3 mA (but do not exceed 7 and 27 kV on the 0 to 10 and 0 to 30 kV supplies, respectively). Turn on the photomultiplier power supplies and the external monitor. Unless the REGULATION settings have been disturbed (see item E) the system is now ready to respond to input video signals.

D. IMAGE STORAGE

Attach the input signal cable carrying standard composite TV video signals to the "COMPOSITE VIDEO IN" BNC connector on the rear of the GAMMA AMPLIFIER. Turn the CONTRAST and BRIGHTNESS dials on the PRECISION MONITOR to approximately 60. (For further information on these settings see item F). Place the system in the WRITE mode and then ENABLE. Check to be sure that the shutters in front of the two photomultiplier detectors are closed. Press the WRITE OVER-RIDE or FRAME WRITE switches to write continuously or during a precise number of vertical TV frames. (Limits on writing electron beam exposure are indicated in item F.)

E. FOCUSSING ADJUSTMENTS

High-resolution images can be recorded only if the electron beam writing on the cathodochromic layer is properly focussed. To achieve focussing it is necessary that the 2nd anode potential of the MAD tube be set at some precise value relative to the ultor accelerating voltage. In general, one must first select the ultor voltage at which the cathodochromic tube will be operated and then the 2nd anode voltage is varied until the electron beam striking the screen is properly focussed. Various methods might be used to arrive at the optimum 2nd anode voltage; some suggestions are offered below.

It is recommended that the cathodochromic MAD CRT's be operated at ultor and 2nd anode voltages of approximately 24 and 6 kV, respectively. The REGULATOR controls on the power supply were set for these levels prior to shipping. If they were disturbed in shipping and focussing is required, proceed as follows: Turn all VOLTAGE and REGULATOR controls completely counter-clockwise. Then, simultaneously turn the two VOLTAGE controls clockwise until the meters show 6.5 and 25 kV. Turn the ultor REGULATOR clockwise until 0.3 mA of regulator current is indicated by the current meter; the voltage will drop back to approximately 24 kV. (By simultaneous adjustment of the REGULATOR and VOLTAGE controls a setting of 0.3 mA and any selected ultor voltage may be achieved). Now adjust the focus REGULATOR control so that the supply draws 0.3 mA; this should produce a reasonably good focus.

To achieve a more accurate focus, two different methods may be used. The first is a systematic trial and error procedure whereby a resolution test pattern is repeatedly stored using only the minimum exposure required for a reasonably visible image. Between exposures the image is erased and the focus VOLTAGE is slightly modified (with corresponding REGULATOR adjustments). By observing whether the resolution of the stored image is improved or degraded by each adjustment, the setting for optimum focus is easily deduced. In the second method the BRIGHTNESS setting is reduced until the phosphor emission while writing is just sufficient to give an easily visible image. Then, while continuously writing, the 2nd anode voltage can be adjusted to optimum focus by observing the resolution of the phosphor emission image. With the second method care must be exercised to avoid tube damage due to overexposure of the cathodochromic (see item F for permissible exposures).

F. CONTRAST AND BRIGHTNESS SETTINGS

Excessive electron beam exposures on cathodochromic sodalite will cause "burning" in the sense that excessively colored areas cannot be completely bleached back to their original uncolored state. It is therefore important that the MAD cathodochromic tubes not be subjected to excessive exposures. Exposures greater than 20 μcoulombs/in.^{2} should not be used. Permissible exposure levels can be specified through exposure times plus CONTRAST and BRIGHTNESS settings which determine the electron beam current. Typical settings for MAD tube #14-3 are given below; similar settings can be used with #39B and #15C but the beam current should be periodically checked as the tubes age. The <u>maximum</u> exposure time in the table below assumes a 12-in.^{2} raster. These <u>maximum</u> values should be decreased for smaller raster areas. CONTRAST settings in excess of 70 should not generally be used. For very fast writing (1 or 2 TV frames) the BRIGHTNESS should be set at approximately 80.

CONTRAST	BRIGHTNESS	CURRENT (μA)	MAXIMUM EXPOSURE TIME (sec)
60	55	20	12
60	60	40	6
60	65	70	3.5
65	50	20	12
65	55	40	6
65	60	70	3.5

Suppose that one wished to store six overlapping images (as proposed by A. Schulman of NASA Goddard). Then one should typically set CONTRAST = 55, BRIGHTNESS = 55, and use FRAME-WRITE set at 8 to store each image.

G. IMAGE READOUT

Place the WRITE-READ switch in READ. Open the shutters in front of the photomultiplier detectors (shutter control levers pulled out as far as possible). Check that the photomultiplier power supplies are turned on with applied voltage of approximately 1 and 1.3 kV on the I and I_0 detectors, respectively. Place the DISABLE-ENABLE switch in ENABLE. Increase the READOUT PHOS. EXC. LEVEL until a readout image is displayed on the external PICTURE MONITOR. This will occur at 60% to 80% of the maximum setting. In this mode (which is the most convenient for many applications) the detected image is continuously displayed without operator intervention.

To obtain the readout image most pleasing to the observer, several adjustments can and should be made. First, the PHOS. EXC. LEVEL may be adjusted; this modifies the contrast in the displayed image. Simultaneous adjustment of the picture monitor brightness and contrast controls is also frequently desirable. Next, the CORRECTION GAIN can be adjusted. Increasing this gain tends to remove granular noise in the reconstructed image; a simultaneous increase in PHOS. EXC. LEVEL is usually desirable. If the picture tends to roll or tear, the SYNC. GAIN should be adjusted.

To use the READ OVER-RIDE or FRAME READ modes the READOUT PHOS. EXC. LEVEL should first be turned to zero and then slowly increased while the READ OVER-RIDE is depressed. The required PHOS. EXC. LEVEL setting is determined by adjusting for an optimum readout. At this optimum setting FRAME READ can be used.

H. PHOTOGRAPHING INCOMING DATA

Remove the plug on the top of the beamsplitter box in the optical system and mount a Nikon F camera as discussed in the FINAL REPORT. Use the knob on the bottom of this box to rotate the photography mirror into position to reflect phosphor emission light to the camera lens. At low BRIGHTNESS settings (or beam currents) in WRITE mode, focus on the image due to phosphor emission. The system is now ready to photograph incoming data.

The proper lens opening and exposure time are always dependent on the film speed. To get a complete picture (frame) the exposure time must in any case, always exceed 1/30 sec. The following are estimates of optimum exposure:

(i) BRIGHTNESS = 50, CONTRAST = 65, ASA 400 film. Lens at f/4, Exposure Time = 1/2 sec.

(ii) An ASA 400 film normally records a good image at f/8 when the camera exposure time is equal to the writing time required to store a fully exposed image in the cathodochromic layer.

I. MEASURING BEAM CURRENTS

The BNC connector on the 0 to 30 kV half of the high-voltage power supply is provided to measure electron beam currents. This connector is across a 1000-ohm resistor in the ground leg of the power supply. When the REGULATOR control is turned counterclockwise so that the regulation circuit is inoperative, all of the ultor current is drawn through this resistor and the writing current level can be measured by displaying the BNC output on a dc-coupled calibrated oscilloscope. Because there is a large ac ripple on this signal, a 40- to 100-μF (15 V) capacitor from the cable to ground will greatly facilitate the measurement. To measure the reading current (typically 100 nA) it is necessary to use a precision dc voltmeter (e.g., Model 825A Fluke voltmeter) with a very large filter capacitor (e.g., 1000 μF).

J. DETAILED SCHEMATICS AND CIRCUIT DESCRIPTION

The electronic circuits which are used in the cathodochromic display system warrant further discussion and a more detailed description of each circuit will be presented.

As a starting point the reader is referred to the system block diagram (Figure 15). Each of the blocks represents a clearly defined portion of the overall system; it is appropriate to discuss the system as a whole and then the operation of each block individually.

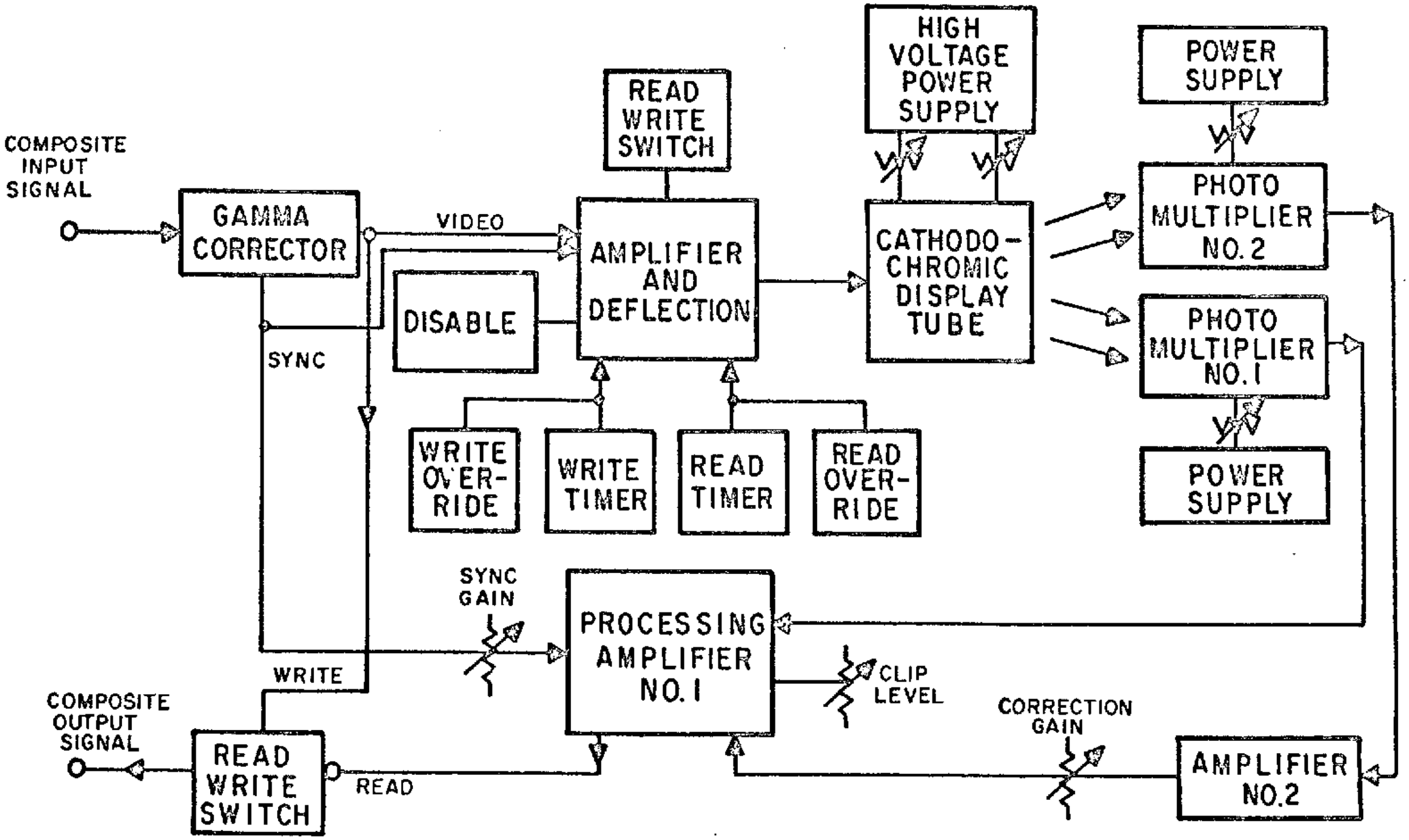


Figure 15. A block diagram of the cathodochromic storage device system.

The heart of the system, of course, is the cathodochromic display tube. This tube is essentially a high-resolution, magnetically deflected kinescope. The electronic requirements of this tube are magnetic deflection fields and the necessary electron gun acceleration, focus and control voltages. In addition, the system operation mode must be changed to provide unmodulated beam current during the information recovery or "READ" operation.

The deflection and signal amplification for the cathodochromic display tube are supplied by a Hewlett Packard precision TV monitor type 6946A. Some modifications were necessary. The kinescope supplied with the monitor was removed and a suitable mounting arrangement was constructed to hold the cathodochromic tube. In addition, the high-voltage power supply was removed and discarded since it does not supply the correct voltages for the cathodochromic tube. Further modifications to the precision monitor circuits are shown in Figure 16. Specifically they are as follows:

(1) A plus 300-volt power supply is added to the monitor. This consists of a transformer, rectifiers, filter, and zener diode regulator. This supply is used to provide G_2 voltage for the kinescope gun.

(2) The kinescope signals are presented to the gun through a switching network so that the system can be used in either the "WRITE" or "READ" mode of operation. This change is accomplished by means of a 3-pole double-throw relay. In the "WRITE" mode the gun cathode is connected to the monitor video circuits, the grid G_1 is connected to the monitor brightness control, and the monitor works as a normal receiver except for the fact that the gun can be turned "ON" or "OFF" by application or removal of G_2 voltage as controlled through B by the "DISABLE-ENABLE" switch on the control panel. In the "READ" mode of operation the cathode is switched to a constant current control which is called "READ PHOS. EXC. LEVEL". G_1 is dc grounded and the remaining relay contact changes from the "WRITE" timing circuits to the "READ" timing circuits.

(3) A pulse-forming network is added to take information from the vertical deflection system and provide a pulse suitable for driving the timer counting circuits.

(4) A video signal relay is added to switch the external video monitor from the incoming video signal during "WRITE" to the signal derived from the cathodochromic tube during "READ".

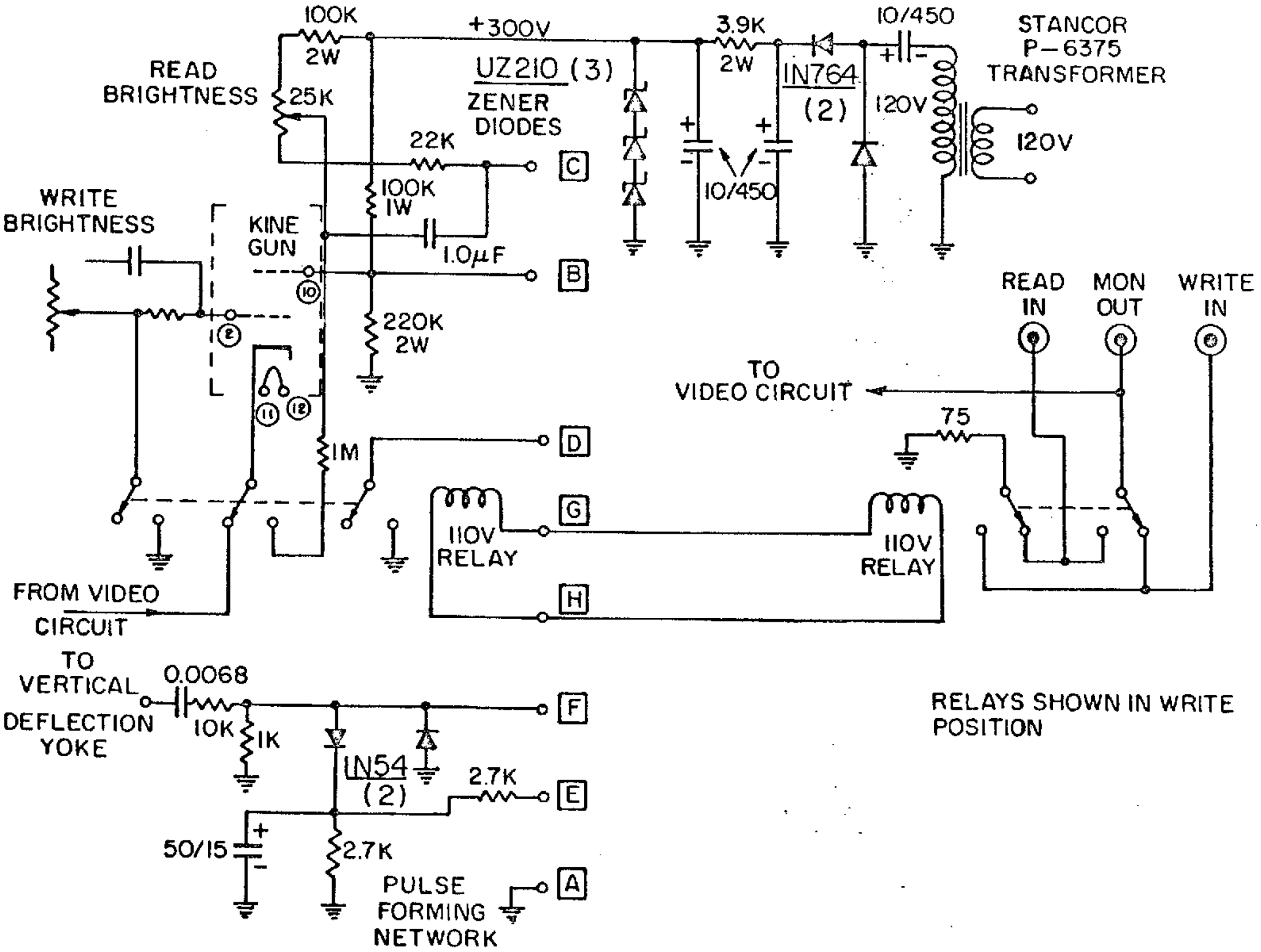
(5) A cable is added to allow connection to the various operating controls which are located on the main control panel (shown in Figure 20). The signals carried on the control cable are as follows:

Terminal A - ground

Terminal B - G_2 control voltage ("WRITE" keying signal (0 or +200 V)

Terminal C - "READ" keying signal (0 or 3 V)

Terminal D - "WRITE"-"READ" timer change (0 or + 1 V)



RELAYS SHOWN IN WRITE POSITION

Figure 16. Schematic diagrams showing circuit modifications to the precision monitor.

Terminal E - + 4.5 volts

Terminal F - 60 cycle pulse to timer circuits (amplitude 2 volts)

Terminal G - 110 volts

Terminal H - 110 volts

This completes the changes to the TV monitor chasis. Some of the controls were moved to the back panel, but otherwise the remaining circuits are as described in the H/P operating manual for the monitor.

The high-voltage power supply for the cathodochromic display tube is a completely separate unit. It should be treated with care as it supplies voltages which are dangerous and even lethal. It comprises two supplies, one for the focus electrode which requires about 6 kV and the other for the ultor which may run as high as 27 kV. Both supplies are fully adjustable and regulated for both line and load variations. The schematic is shown in Figure 17. The two supplies are similar in operation with the exception that one operates in the 0-10 kV range and the other in the 0-3 kV range. The reference voltage for the regulator is derived from a 300-V zener-diode-regulated source. The high-voltage regulator is a shunt type regulator which means it is in parallel with the kinescope load and it draws an appropriate current to maintain the output voltage at a fixed level. Metering is provided to observe the output voltage and the regulator current. Setup procedure is as follows: Increase the variac voltage control until the output voltage is about 1 kV higher than the desired value. Then increase the regulator control until the regulator draws about 300 μA of current or the voltage decreases to the desired value. At all times observe the following procedure: turn voltage control down when not in use. Increase voltage as the last step in turning the system "ON" and as the first step in turning the system "OFF". Allow time (1 minute) between turning on power switch and increasing voltage control so that the tubes can warm up and come to operating condition. If the cover to the power supply is removed for any reason, extreme caution to avoid contact with high-voltage components is essential; no interlock protection is provided. Also exercise all possible caution to ensure that the kinescope gun and the deflection circuits are operating before turning up the high voltage, or serious damage to the tube can result, especially in the absence of deflection.

The next portion of the system to be discussed is the input signal gamma corrector. As mentioned elsewhere in the report, the cathodochromic material is highly nonlinear in its characteristic of light absorption VS activation energy. In order to restore linearity to the system, it is necessary to create a compensating non-linearity in the electronic signal processing; this is the function of the gamma corrector.

Refer to Figure 18 for the gamma corrector block diagram and to Figure 19 for the corresponding schematic diagram. Operation is as follows: The power supply consists of a zener-diode-regulated +10 V conventional unit. The input and output signals to the gamma corrector are nominally 1 volt peak to peak,

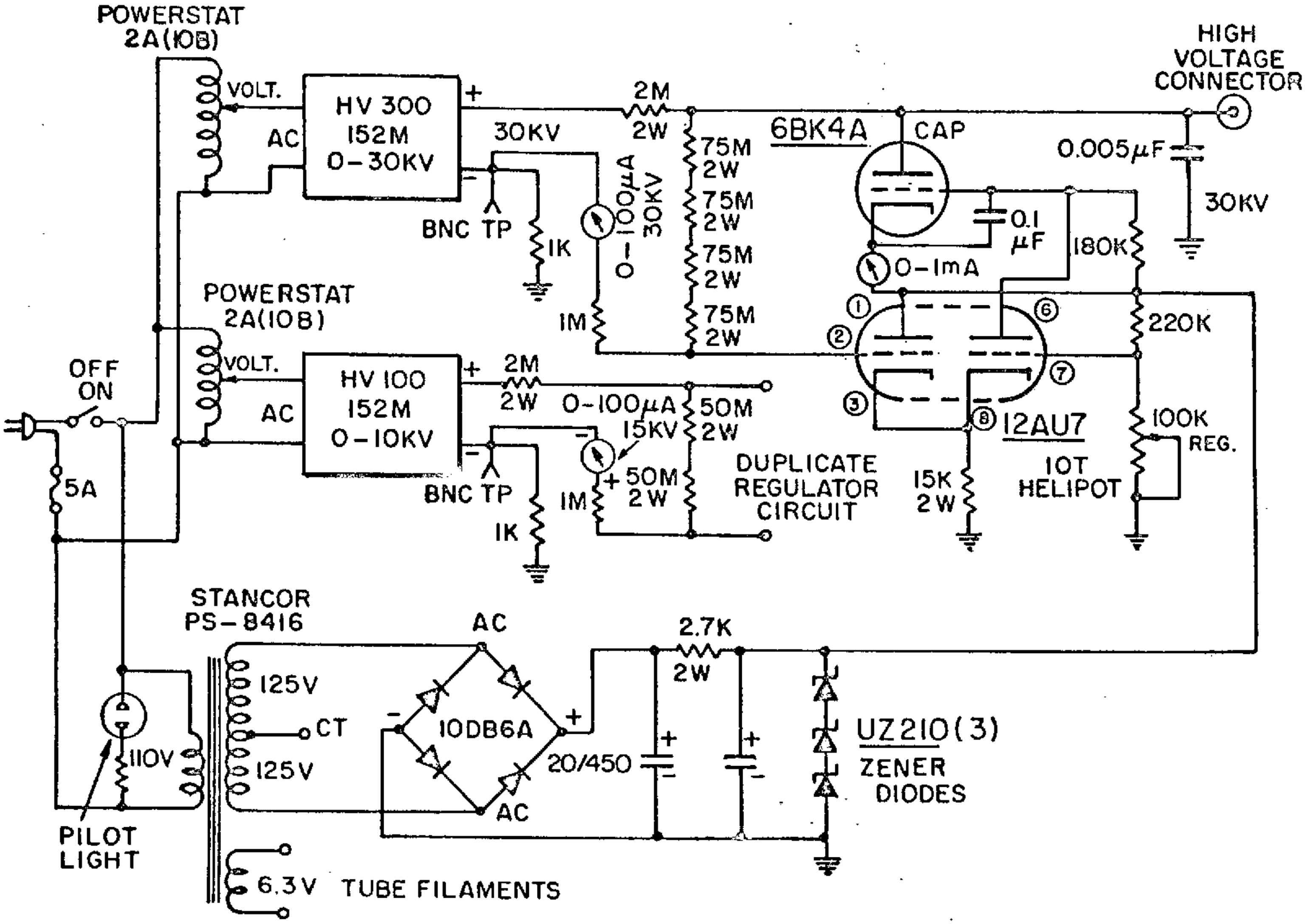


Figure 17. Circuit diagram of the regulated dual power supply unit.

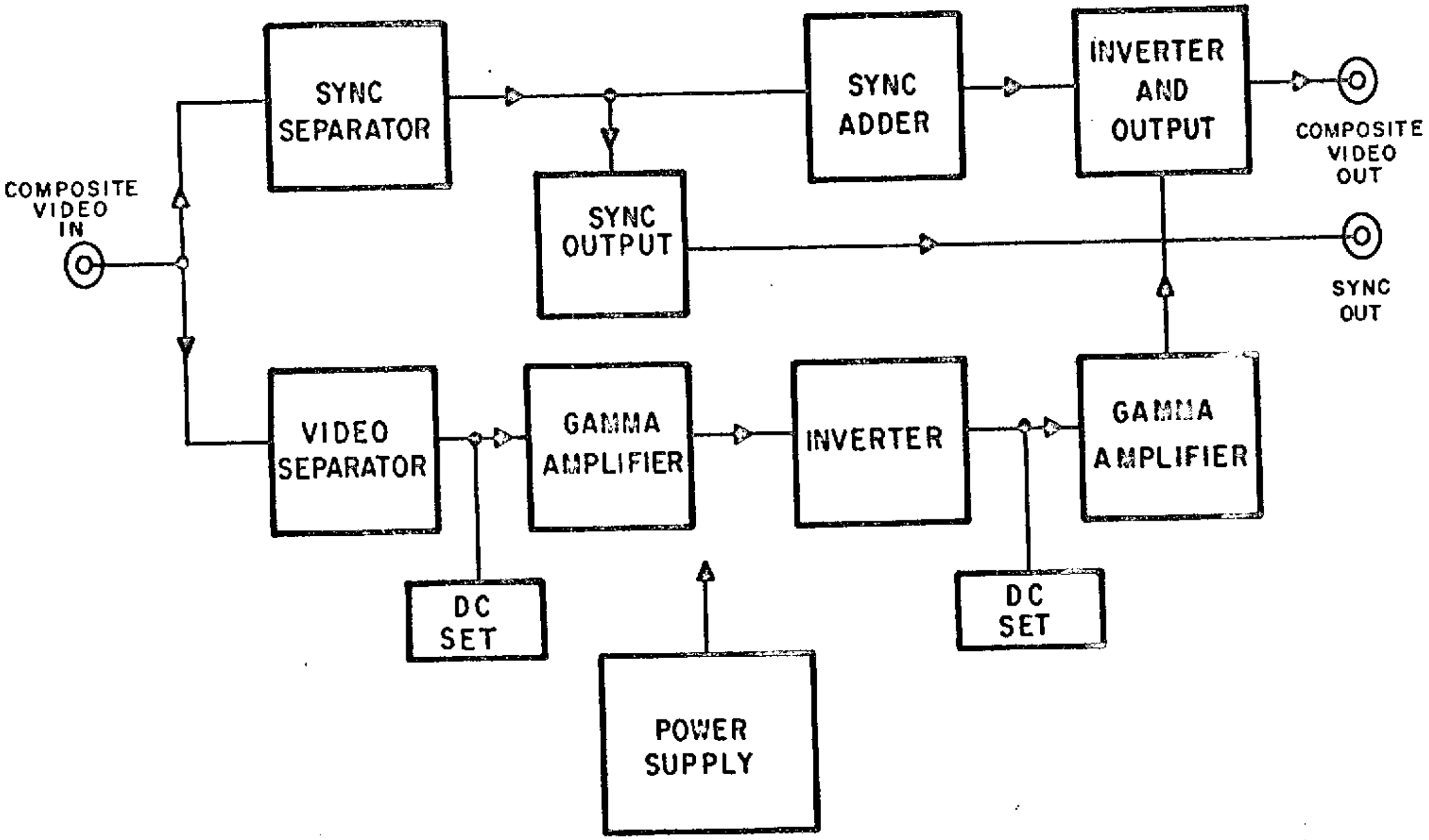


Figure 18. A schematic block diagram of the gamma corrector amplifier.

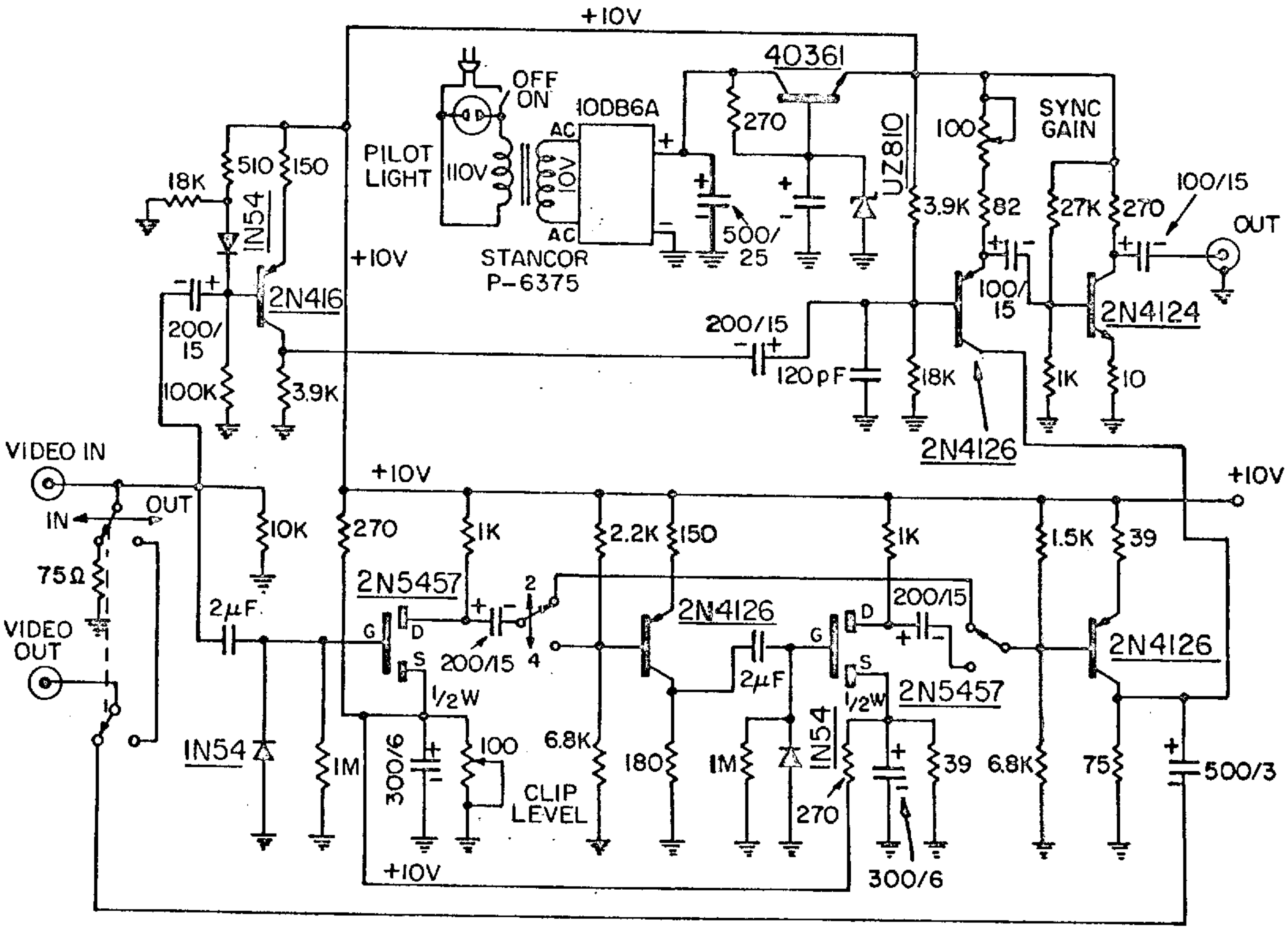


Figure 19. A detailed circuit diagram for the gamma corrector amplifier.

75-ohm source, 70% video, 30% sync, standard TV distribution signals. It is important that the signals conform fairly closely to these standards in order that the clipping, sync amplification and gamma correction occur on the correct portions of the signal. The input signal follows two paths. The upper path is the sync portion of the amplifier. This amplifier is dc set to pass only the most negative or sync portion of the signal. Stripping of the sync is necessary because the sync signals should not be gamma-corrected; they are later readded to the corrected video. In addition, a separate sync output terminal is provided to supply sync information to the deflection portion of the H/P monitor and to the processing amplifier where it is added to the signal generated during the "READ" mode of operation. This makes the read signal a composite of video information plus sync so it is suitable for driving other TV picture monitors. The lower portion of the amplifier is the video gamma corrector. The input signal is dc set by the first clamp diode which is located on the gate of the input field effect transistor. The source of the FET is returned to an adjustable dc level which is nominally set to make the black level of the signal correspond with drain current cutoff of the FET. When adjusted in this manner the drain current is then approximately related to the gate voltage as $I_D = KE_G{}^2$. This provides a square law correction of linearity as desired. The signal is then inverted because the correction FET has already provided one inversion. The process is repeated by a second FET to provide fourth power correction. The output amplifier supplies the final inversion so the signal is the same polarity as at the input. Two switches are provided to select corrections of linear, square law, or fourth power. This is accomplished by bypassing one or both of the gamma correction amplifier stages.

As has been mentioned several times, the system has two modes of operation. The first mode of operation is to store information or "WRITE" on the cathodochromic tube. Secondly, it is desired to recover the information which has been stored in the "WRITE" mode. This, of course, is called "READ".

The control panel (Figure 20) contains the selection switches to change the mode of operation as well as the timing and the "READ" signal-processing circuits. In addition, the power supplies for the "READ" signal-processing amplifiers and timers are located on the control panel.

The "WRITE"-"READ" switch controls the 110 V ac to the two relays which are located on the HP monitor chassis. These relays provide the necessary changes to the kinescope gun circuits as well as switching the external monitor from the "WRITE" to the "READ" signals.

The "DISABLE" switch grounds G_2 of the kinescope gun and thus prevents beam current from reaching the kinescope screen regardless of the G_1 and cathode potentials.

The "READ" and "WRITE" override switches function in parallel with the timer outputs to allow gun current for as long as such switch is depressed. Only the designated switch works, depending on the system mode of operation.

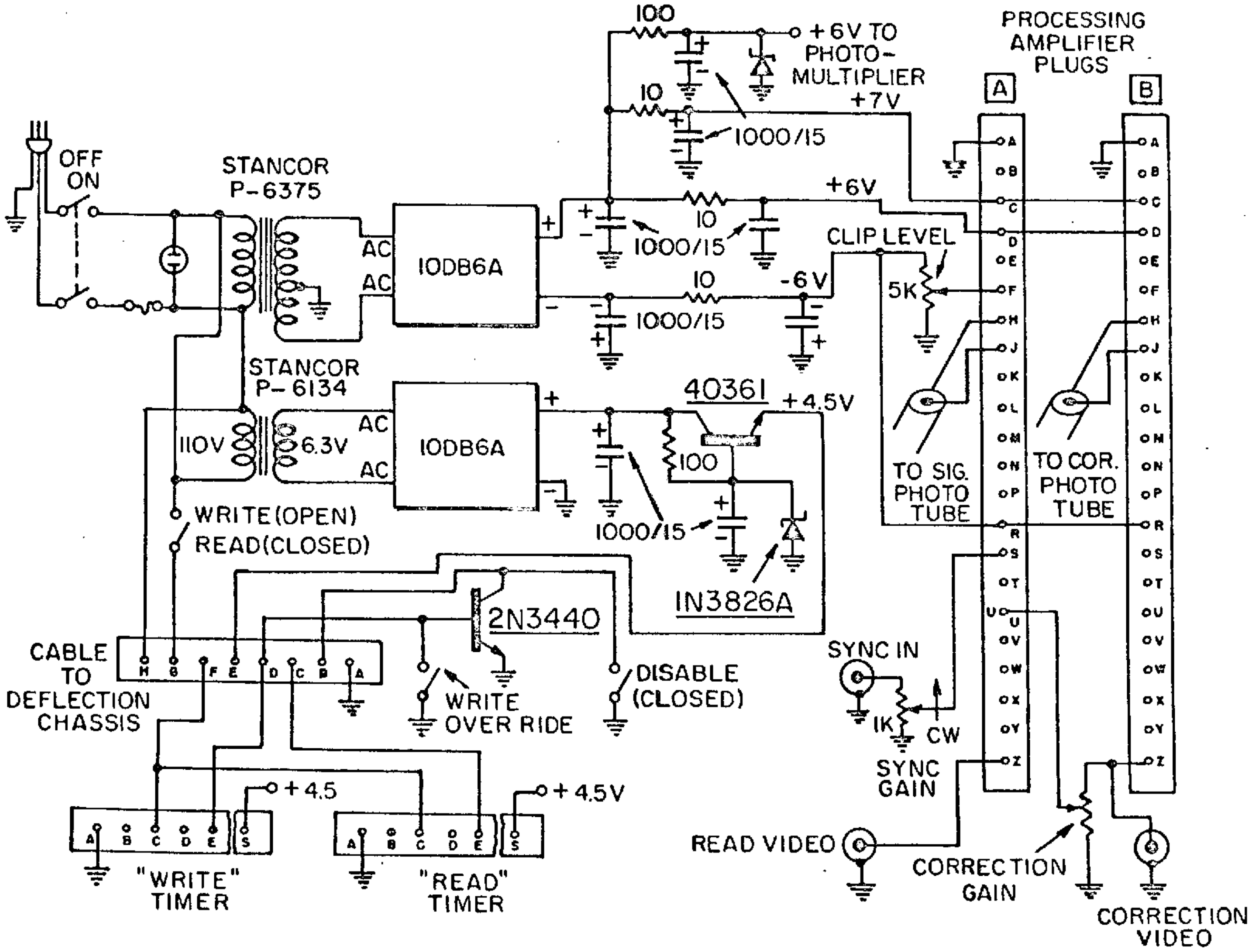


Figure 20. The control panel schematic circuit diagram.

During the "READ" mode of operation the kinescope gun supplies a constant current to the screen during the active scan time. The light from the phosphor layer is modulated by the absorption of the cathodochromic layer and passes through the optical system to the two photomultiplier cathodes. The photomultiplier circuit is shown in Figure 22. It is conventional and requires no further explanation. The purpose of the photomultipliers is to convert the light signals to electrical signals which are then coupled through emitter followers to reduce to impedance level. The signals are transmitted on cables to the signal processing amplifiers (Figures 21 and 22) which are located on the main control panel (Figure 20). The signal level on the coupling cables is about 10 millivolts. There are two processing amplifiers. The processing for the correction signal is performed by board "B" which amplifies the signal by a factor of 100 and delivers it to the output terminal through a low-impedance drive amplifier. The gain of 100 is provided by a Texas Instrument IC amplifier type SN7510L which has a bandwidth of at least 10 MHz. The signal amplifier "A" is somewhat more complex in that, in addition to the gain of 100, it provides clipping, peaking, signal correction, and sync adding. The clipping and peaking are provided by the transistor amplifier immediately following the integrated-circuit amplifier. Clipping level is adjusted by changing the base bias voltage connected to terminal F. The most positive portion of the signal extends into the cutoff region of the transistor operating characteristic and is therefore clipped off. The collector load is frequency-dependent because of the 100-μH inductor and so provides additional gain in the 3- to 4-MHz region of the frequency spectrum. The signal correction portion of the amplifier is the transistor type 2N4124 immediately following the peaking and clipping stage. The function of this amplifier is to provide a variable gain in response to the signal from the correction channel. This is accomplished by using a field-effect transistor as the ac emitter resistor of a conventional RC-coupled amplifier. The effective resistance which the FET presents is a function of its gate voltage and therefore the gain of the configuration for small signals is a linear function of the gate voltage on the FET. This provides the approximate correction desired. The final transistor of the amplifier is a low-impedance output stage with provision for adding sync. At terminal Z this yields a composite signal of video and sync with 1-volt amplitude and at 75-ohm impedance.

The final portion of the system electronics is the timer. There are two identical timers, one for "WRITE" and one for "READ". They consist of integrated-circuit counters which use the Motorola series MC700 IC's (flip-flops and dual-input gates). The basic idea is that a pulse is derived from the vertical retrace interval of the monitor. A simple counting of these pulses determines the number of fields which have been presented. Depressing the "WRITE" or "READ" switch resets the counters to zero. Releasing the switch allows the counters to proceed. An output pulse is generated which starts at the first retrace pulse following release of the switch and continues for twice the number of retrace pulses as indicated on the time switch. The factor of two is included because there are two interlaced fields to make a complete frame, and the time switch indicates number of frames - each frame being about 1/30 of a second in duration. The schematic of the timer is shown in Figure 23.

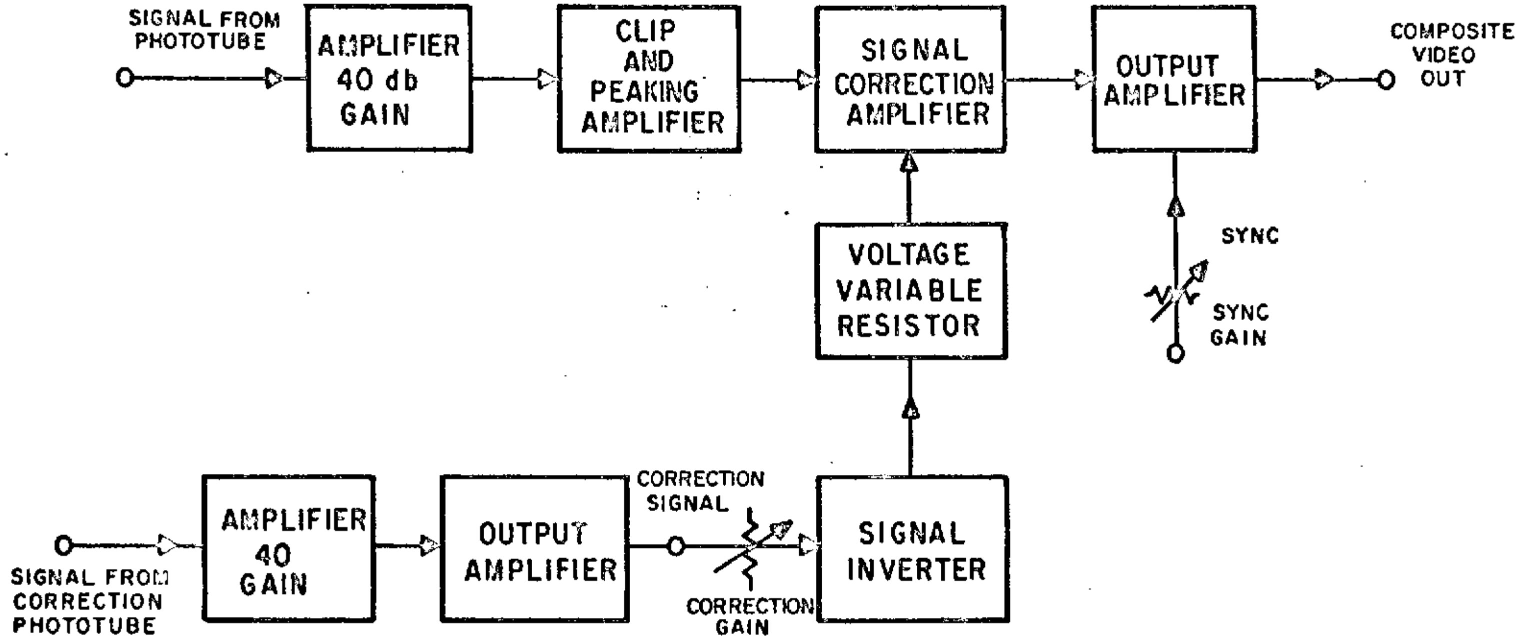


Figure 21. A schematic block diagram of the processing amplifiers.

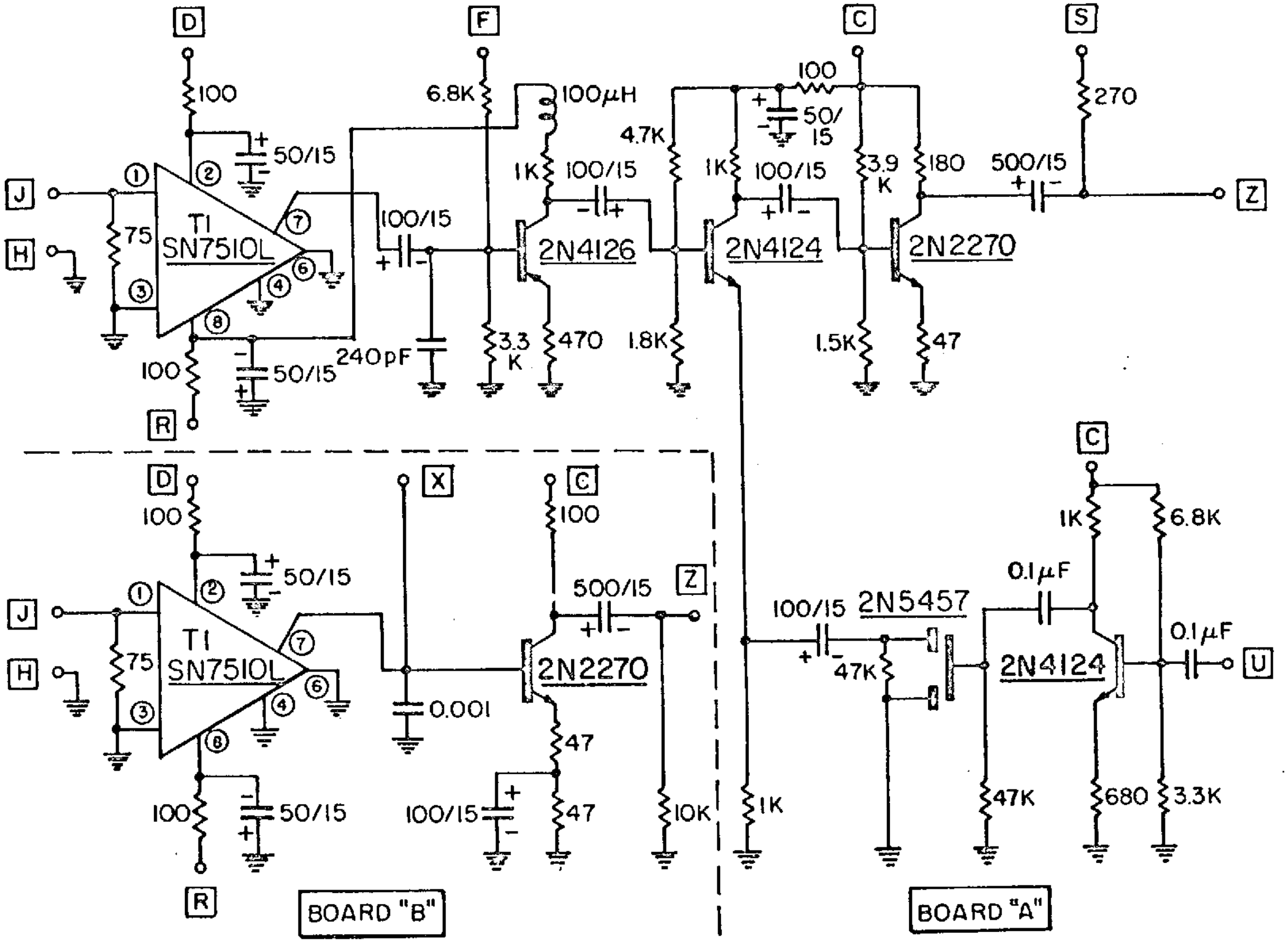


Figure 22. Detailed circuit diagrams for the processing amplifiers.

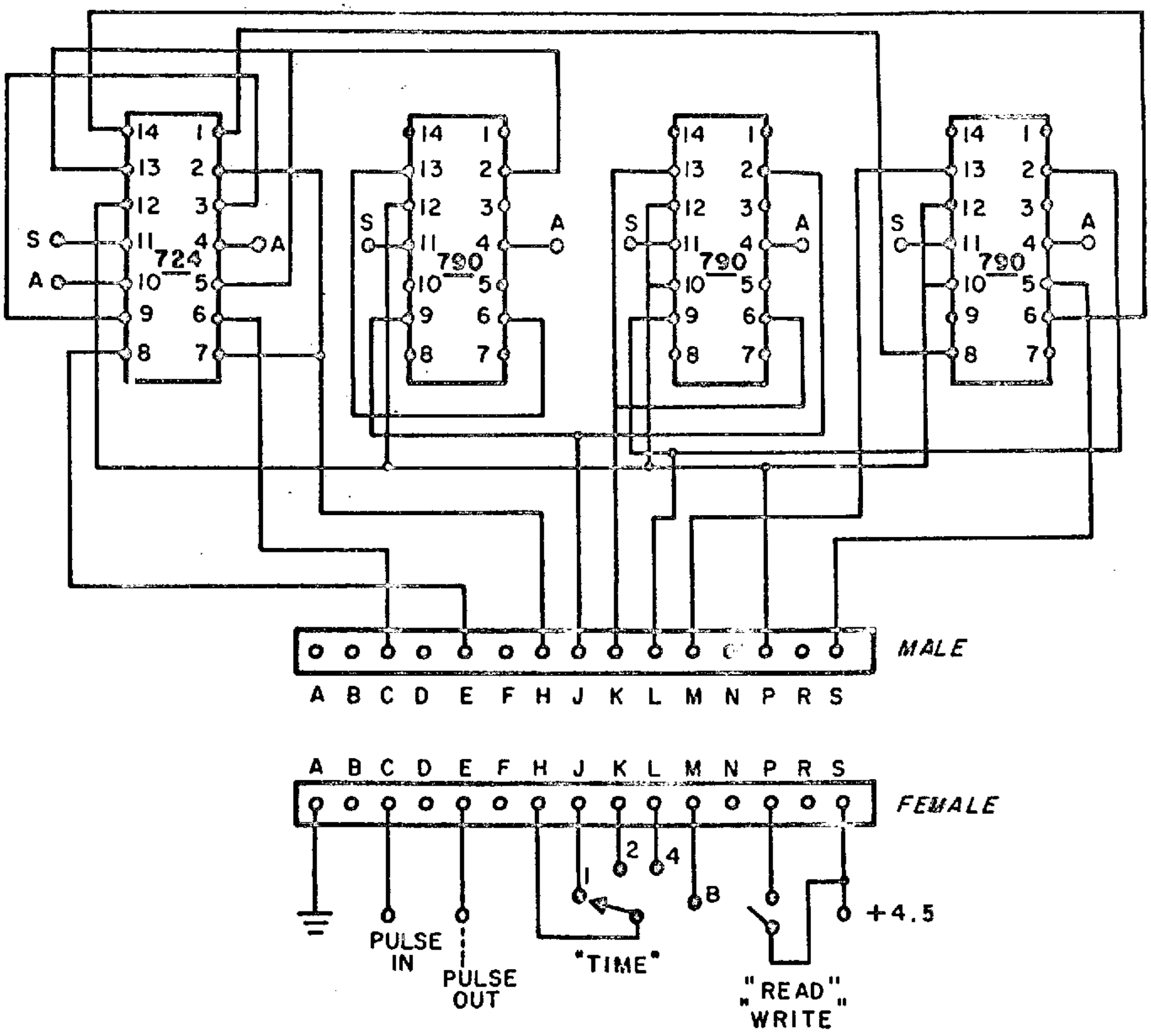


Figure 23. A schematic diagram of the vertical frame timer.

In Figures 24, 25, and 26 we show the photomultiplier circuit, the alarm circuit, and the cabling diagram; these are self-explanatory.

K. PRECAUTIONS AND TROUBLE SHOOTING

A few words are in order to describe precautions which should be observed and possible hints to help locate malfunctions.

1. Observe all possible care with the high-voltage power supply. It is dangerous. Always turn it "on" last and "off" first in operating the system. Turn "off" and "on" by reducing the voltage controls to zero - not by turning the power switch "off" and "on". Any corona discharge from the high-voltage power supply caused by dirt or moisture either in the supply or around the high-voltage cap on the kinescope will result in noise flashes in the video signals. Also, application of high voltage to the kinescope in the absence of deflection will certainly damage the kinescope.

2. An alarm circuit is provided to sound a buzzer if the optical system is open to light and the photomultiplier shutters are not closed. The photomultipliers are easily damaged by excessive light and therefore should be protected from high illumination levels at all times.

3. Any high-voltage arcing can cause damage to the circuit transistors, especially the G_2 keying transistor type 2N3440 and the monitor video output transistors. In the event that no beam current can be obtained, check these transistors, especially the type 2N3440.

4. A high-voltage electron beam will always generate X-rays. The present cathodochromic storage device in a typical high current mode (writing at 150 µA) generates less than 3 milliroentgen/hour of X-rays at a distance of 2 inches from the MAD CRT faceplate. This is well within the range of permissible occupational exposure rates as quoted by the American Institute of Physics Handbook (2nd Edition, 1963, page 8-320). These data combined with the fact that writing time is a small fraction of the total operating time, leads to the conclusion that the MAD CRT does not represent a significant X-ray hazard.

5. Like other high-voltage devices, the 5ZP16 requires that certain precautions be observed to minimize the possibility of failure due to humidity, dust, and corona. The tube itself has certain features designed to suppress corona, arc-over, and high-voltage leakage so that maximum life and optimum performance will result if the following precautions are observed.

<u>Humidity Considerations</u>. When humidity is high, a continuous film of moisture may form on untreated glass. If a high-voltage gradient is present, this film may permit sparking to take place over the glass surface. In order to minimize the formation of a continuous moisture film, the glass cone of the 5ZP16 is treated with a transparent moisture-repellent insulating coating. This coating must not be scratched, and must be kept clean and free from contamination such as fingerprints. The coating may be washed with a solution

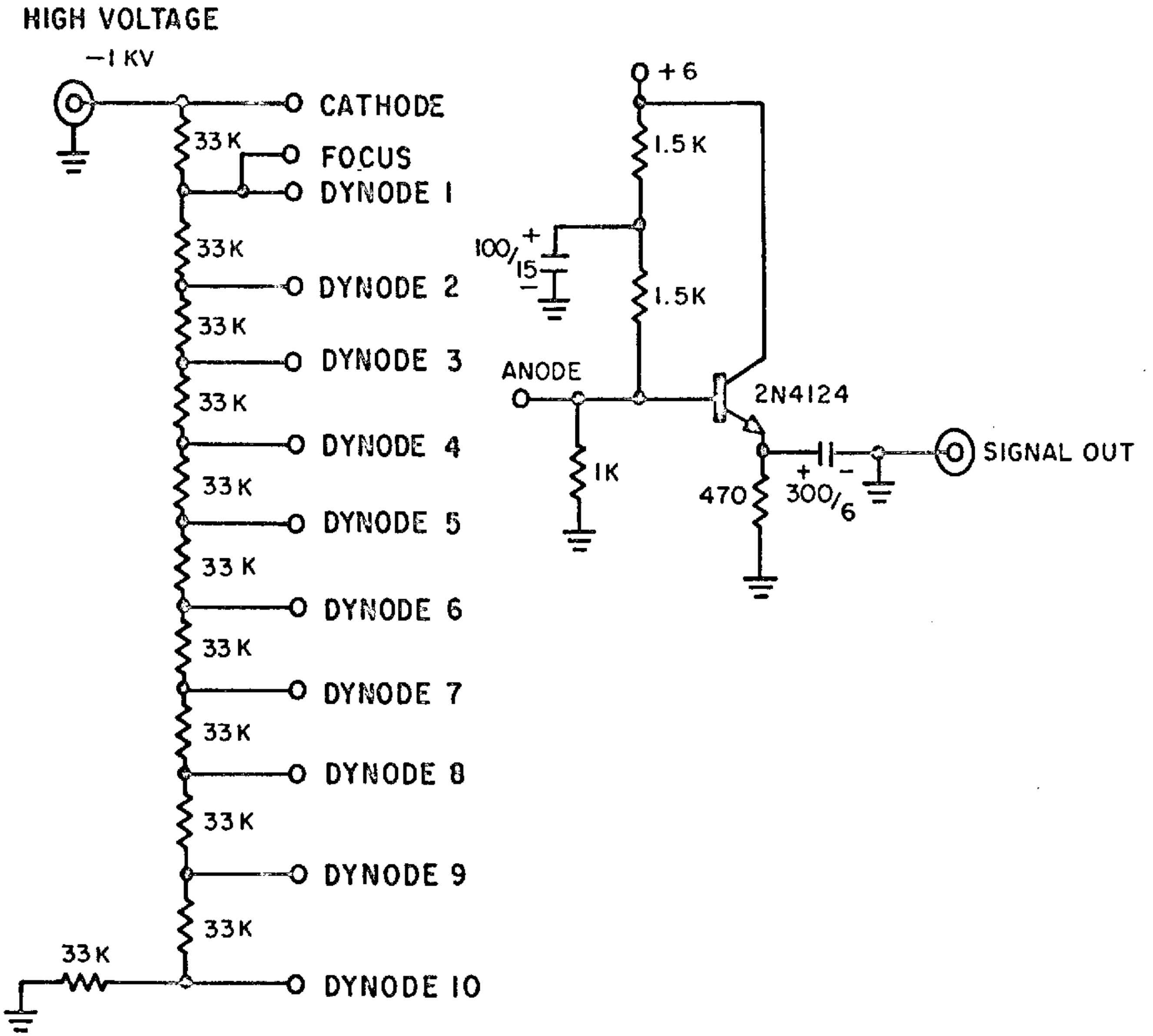


Figure 24. A schematic diagram of the photomultiplier dynode biasing circuit and the impedance-matching emitter-follower output circuit.

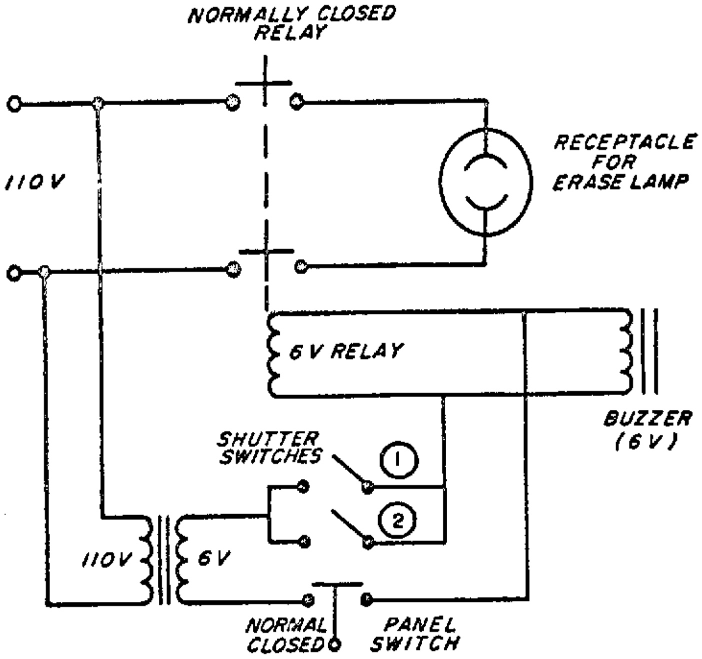


Figure 25. An alarm circuit which sounds a buzzer and turns off the erase lamp when the photomultipliers are exposed to ambient light.

of a mild soapless detergent and water. After the surface is washed, it should be rinsed with clean water and be dried immediately. Any damage to the coating or any contamination on the surface may result in sparking over the cone of the bulb.

Dust Considerations. The high voltage applied to the 5ZP16 increases the rate at which dust is precipitated on the surface of the tube. The rate of precipitation is further accelerated in the presence of corona. Such dust not only decreases the insulation of the bulb coating but also reduces the amount of radiation transmitted through the bulb face. The dust usually consists of fibrous materials and may contain soluble salts. The fibers absorb and retain moisture; the soluble salts provide electrical leakage paths that increase in conductivity as the humidity increases. Because a film of dust can nullify the protection provided by the insulating coating on the bulb, the 5ZP16 should be protected as much as possible from dust and should be cleaned, when necessary, as described under Humidity Considerations.

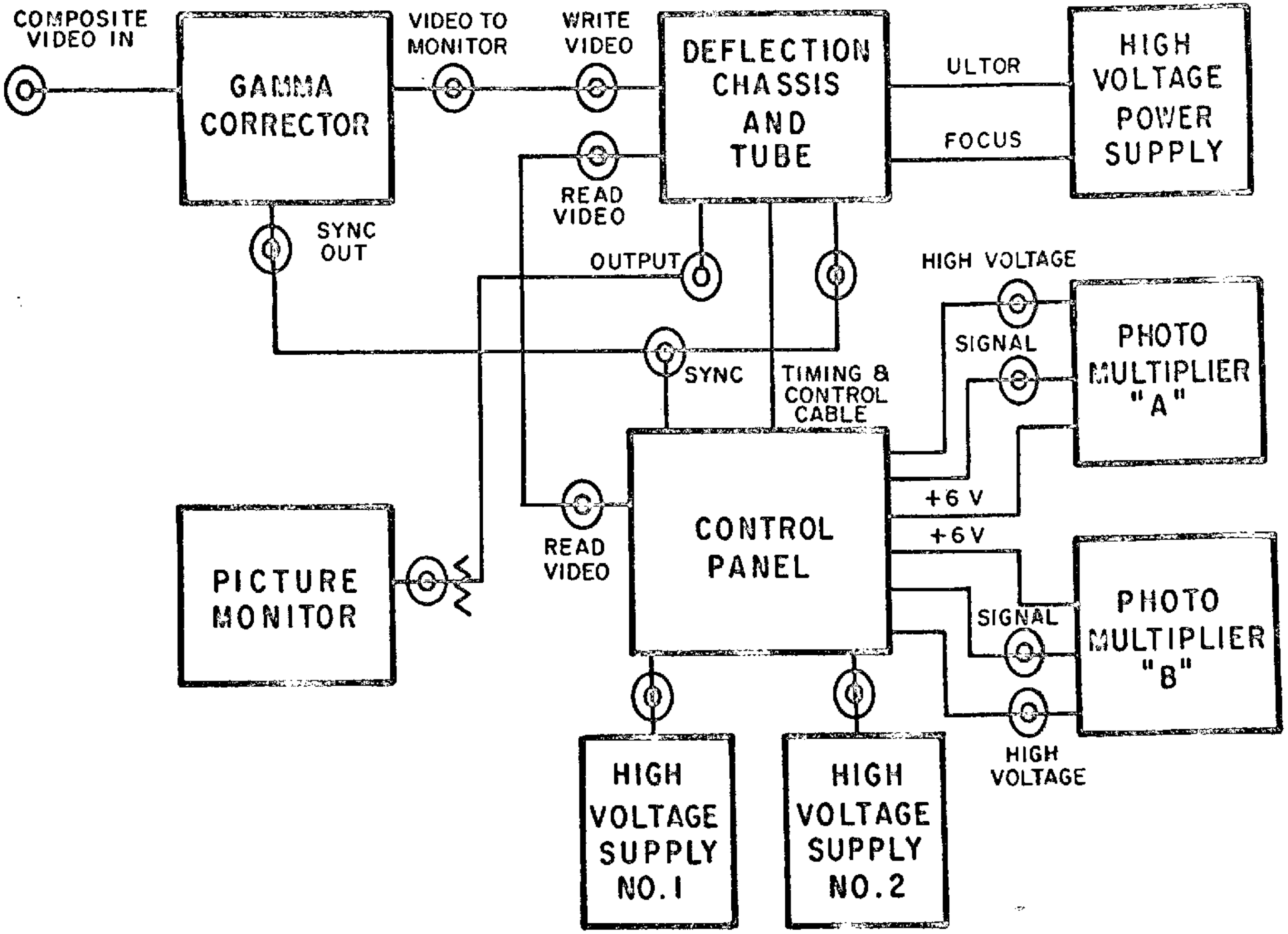


Figure 26. The cabling diagram for the complete system.

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1. D. R. Bosomworth and W. Phillips, First Quarterly Report, August 1968, Contract No. NAS 5-10636.

2. D. R. Bosomworth and W. H. Moles, Second Quarterly Report, January 1969, Contract No. NAS 5-10636.

3. D. R. Bosomworth and W. H. Moles, Third Quarterly Report, May 1969, Contract No. NAS 5-10636.