ERRATA - October 1964

The following corrections apply to Technical Documentary Report No. AMRL-TDR-64-49, Development of Techniques for Evaluation of Visual Simulation Equipment.

Page 48

Change the second sentence of paragraph 4. to read:

> The waveform first observed on the oscilloscope was masked by random, high frequency noise. A low-pass, 1.25-mc, 3-db cutoff filter was inserted to eliminate this noise, but the insertion again raised the question of bandwidth adequacy.

Page 64

Change the second sentence of paragraph 2 to read:

> For instance, in a 1029 scanning line system with a 60-cycle-per-second field rate interlaced 2 to 1, the time per scanning line is reduced to $\left[1/1029/2\right] / 60 = 1/1029 \cdot 30 = 1/30,870 = 32.4$ microseconds per line.

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DEVELOPMENT OF TECHNIQUES FOR EVALUATION OF VISUAL SIMULATION EQUIPMENT

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FOREWORD

This study was initiated by the Behavioral Sciences Laboratory of the Aerospace Medical Research Laboratories, Aerospace Medical Division, Wright-Patterson Air Force Base, Ohio. The research was conducted by the Systems Research Laboratories, Inc. (SRL) of Dayton, Ohio 45432, under Contract No. AF 33(657)-8299. Phase I research, performed by John F. Feltz and Jerome I. Wysong, and Phase II research, performed by Jerome I. Wysong, was conducted under the direction of SRL Senior Engineer John H. Harshbarger. Arthur T. Gill of the Simulation Techniques Branch, Training Research Division, Behavioral Sciences Laboratory, was the contract monitor for the Aerospace Medical Research Laboratories. The work was performed in support of Project No. 6114, "Simulation Techniques for Aerospace Crew Training," Task No. 611405, "Visual Simulation." The research sponsored by this contract was initiated in March 1962 and completed in April 1964.

The author acknowledges the contribution of Arthur B. Doty, Jr, formerly of AMRL, in initiating, organizing, and assisting in the early stages of the study.

This technical report has been reviewed and is approved.

WALTER F. GRETHER
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ABSTRACT

In Phase I of this report, a study of large area image display by projection television was undertaken to evolve techniques of suitable image generation for astronautical flight simulation training. It was necessary to develop a technique to evaluate projected images. The display provided by the research apparatus, the close-circuit television system from an F-151 Fixed Gunnery Trainer, was evaluated; and performance characteristics of the 7WP4 performance in an ultra-high resolution television system revealed the tube to be unsuited to high resolution service. In Phase II of this report, the projector in the F-151 television system is converted from a conventional 525-line system to a high resolution 1029-line system. The 525-line format operated at 30 frames per second, with a horizontal scanning frequency of 15.75 kc and a vertical scanning frequency of 60 cps. In the 1029-line system, the frame rate and vertical scanning frequency were retained, but the horizontal scanning frequency was changed to 30.87 kc. The vertical sweep generator, sweep protection, and projection control circuits were duplicated; a video amplifier and horizontal sweep generator were developed; and volume of the control equipment was reduced from 144 to 32 cubic feet. Performance of the 7WP4 tube exceeded the prediction: limiting horizontal resolution is 650 to 700 lines with a well defined vertical raster. Research indicates that a study into basic CRT characteristics is in order, particularly for use in display devices.

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PHASE I

EXPLANATION OF TERMS

General Description. The television raster, which is generated on the cathode-ray tube or other display device, is a scanning by the movement of the picture information signal (scanning line) across the raster from left to right (of the viewer) and top to bottom and is blanked during the return movement from right to left and bottom to top. These movements are set by the synchronizing signal in a pattern (field) of spacing which spaces the scanning lines of one field far enough apart so that the scanning lines making up the pattern of a second field can be inserted as interlace between the original lines. In current conventional systems, one field is scanned in a period of 16.667 milliseconds. Two fields, making up one frame, are scanned in 33.334 milliseconds.

Alignment. In the case of television camera tubes, precise alignment of the electron beam to be exactly perpendicular to the plane of the photosensitive surface. Proper magnetic field adjustment of this type is necessary for best focus and resolution over the entire usable area of the photocathode.

Aspect Ratio. In television, the ratio of the picture width to the picture height.

Bandwidth. That portion of a frequency spectrum that is required or made available for proper transmission of the signal of interest.

Beam. A stream of electrons in a vacuum tube flowing from an emitting electrode to a collecting electrode or surface.

Bit. Generally, the arbitrary designation for a unit of information. Specifically, as applied to television, it is the smallest resolvable element of a scanning line.

Blanking Level. That level of a composite picture signal which separates the picture information from the synchronizing information.

Blanking Signal. A wave constituted of recurrent pulses used to effect blanking, that is, suppress brightness, during certain periods. In television, this blanking signal is composed of pulses originating in a central sync generator and is combined with the picture signal at the

pick-up equipment to form the blanked picture signal (a term for the combination of the blanking signal and the picture signal). The addition of the sync signal completes the composite picture signal.

Bleeding White. An overload condition of a vidicon camera tube photosensitive surface in which areas appear to flow irregularly into black areas.

Blooming. An increase in the beam spot size caused by an increase in signal intensity. The effect is a degradation in the quality of the picture.

Brightness. The attribute of visual perception related to the intensity of a light source. The term "brightness" has previously been used for both photometric quality and for the sensory response of the eye to light. This use of the same term for two wholly different concepts has confused photometric quantity with the non-quantitative sensation.

It has therefore been recommended that "luminance" be applied to the concept of photometric quantity and that "brightness" be reserved for sensations and perceptions of light. For example, it is correct to refer to a "brightness match", even in the case of a photometer, because the sensations are matched and because only by inference are the photometric quantities (luminances) equal. Likewise, a photometer in which such matches are made will continue to be called an "equality-of-brightness" photometer. A photo-electric instrument calibrated in foot-lamberts, however, should not be called a "brightness" meter; if correctly calibrated, it is a "luminance" meter. The "luminance" of a surface may be doubled, but the "brightness" is not doubled since the sensation of brightness can not be judged to be doubled.

Camera Tube. An electron tube used for the conversion of a visual image into an electrical signal.

Composite Picture Signal. The signal which results from combining picture information, blanking signals, and synchronizing pulses.

Contrast. The range of light and dark values in a picture or the ratio between the maximum and minimum values of brightness.

Density. A measure of light-transmitting or reflecting properties of materials or surfaces. However, the manner in which different materials are measured will differ, e.g., the density of film or glass, and there is, therefore, a variety of units of measure of density.

Detail Contrast. Measure of the contrast obtained in higher resolution, fine pattern picture areas as opposed to that obtained in lower resolution, coarse pattern picture areas, usually expressed as a percentage at a particular number of lines of resolution.

Field. A field is the picture area scanned in a chosen pattern of scanning lines. In interlaced television scanning, the scanning lines of any one field are widely spaced, usually a distance of two or more times the nominal line width to allow space in which to place the lines of another or successive field.

Focus, Optical. The position in which something must be placed to obtain clarity of visual perception.

Focus, Electron. The point at which electron beams converge. Adjustment must provide this convergence at the tube surface for optimum performance.

Footcandle. A unit of illuminance in which the foot is the unit of length. One footcandle is the measure of the illuminance on a surface one square foot in area on which there is a uniformly distributed light flux of one lumen or is the illuminance at a surface all points of which are at a distance of one foot from a uniform source of one candle.
NOTE: illuminance is incident light.

Foot-Lambert. A unit of luminance equal to $1/\pi$ candle per square foot of the uniform luminance of a perfectly diffusing surface emitting or reflecting light at the rate of one lumen per square foot.
NOTE: luminance is emitted or reflected light.
In the case of a perfectly reflecting and perfectly diffusing surface, the number of footcandles of illuminance would equal the number of foot-lamberts of emitted or reflected light.

Frame. A frame is composed of two or more fields, generally restricted to no more than three, although a greater number may be used.

Gaussian. Associated with a process whose probability density function is normal distribution.

Geometric Distortion. Any aberration which causes the reproduced picture to be geometrically dissimilar to the original scene.

Glitch. A form of low frequency interference appearing as a narrow horizontal bar moving vertically through the picture.

Highlights. The maximum brightness of the picture. Highlights occur in regions of highest image illumination.

Horizontal Blanking. The portion of the blanking signal at the end of each scanning line that suppresses display brightness during beam return from the right to the left side of the raster.

Horizontal Retrace. The return of the electron beam from right to left of the raster after the scanning of one line.

Hum. Electrical disturbance at the power supply frequency or harmonics thereof.

Image Dissector Tube. A camera tube in which an electron image is produced by a photoemitting surface.

Image Iconoscope. A camera tube in which an electron image is produced by a photoemitting surface and which employs a separate storage target for image transmission.

Image Orthicon. A camera tube in which an electron image is produced by a photoemitting surface and focused on one side of a separate storage target which is scanned on its opposite side by an electron beam.

Image Tube. An electron tube which reproduces on its fluorescent screen an image of an irradiation pattern incident on its photosensitive surface.

Interlaced Scanning. A scanning process in which the distance from center to center of successively scanned lines is two or more times the nominal line width and in which the adjacent lines belong to different fields.

Ion Spot. A spot on the fluorescent surface of a cathode-ray tube which is somewhat darker than the surrounding area because of bombardment by negative ions which reduce the sensitivity of phosphor spectral output.

Ion Trap. An arrangement of magnetic fields and apertures which will allow an electron beam to pass through but will obstruct the passage of ions.

Jitter. Small, rapid variations in a presentation due to mechanical disturbances, to changes in the supply voltages, or to the characteristics of components.

Lag. A persistence of an electrical-charge image on the screen.

Lambert. A unit of luminance equal to $1/\pi$ candle per square centimeter and equal, therefore, to the uniform luminance of a perfectly diffusing surface emitting or reflecting light at the rate of one lumen per square centimeter.

Lumen. The unit of measure of luminous flux. It is equal to the flux through a unit solid angle (steradian) from a uniform point source of one candle or to the flux on a unit surface, all points of which are at unit distance from a uniform point source of one candle.

Microphonics. Audio-frequency noise caused by mechanical vibration of the elements of a system or component.

Moire. A wavy effect produced by the convergence of lines. It usually appears as a curving of the lines in the horizontal wedges of the test pattern and is most pronounced near the center where the lines forming the wedges converge. A moire pattern is a natural optical effect which appears when the converging lines in a picture are nearly parallel to the scanning lines. To a degree, the effect is caused by the characteristics of color picture tubes and image-orthicon pick-up tubes (in the latter case it is termed "mesh beat").

Monochrome. Absence of color; only shades of grey are present.

Monoscope. A signal-generating electron-beam tube in which a picture signal is produced by scanning an electrode which has a predetermined pattern permanently affixed on the tube electrode surface.

Pairing. A complete or partial failure of interlace. The scanning lines of alternate fields do not fall exactly between one another but instead tend to fall one on top of the other (in pairs).

Photocathode. An electrode used to obtain photoelectric emission.

Picture Tube. A cathode-ray tube used to produce an image by variation of the beam intensity as the beam scans a predetermined area of a light-emitting phosphor.

Preamplifier. An amplifier with the primary function of raising the output of a low-level signal source to an intermediate level so that the signal may be further processed without appreciable degradation in the signal-to-noise ratio of the system.

Random Interlace. In random interlace there is no fixed relationship between adjacent lines and successive fields.

Raster. A predetermined pattern of scanning lines which provides substantially uniform coverage of an area of a display surface.

Raster Burn. A change in the characteristics of that area of the surface which has been scanned resulting in a spurious signal when other areas are scanned.

Resolution (Horizontal). The amount of resolvable detail in the horizontal direction of a picture. It is usually expressed as the number of distinct vertical lines (alternately black and white) which can be seen in a horizontal dimension equal to the picture height.

This information is usually derived by observation of the vertical wedge of a test pattern. A sharp and clear picture which shows small details has good or high resolution. A soft or blurred picture in which small details are indistinct has poor or low resolution. Horizontal resolution depends on the high-frequency amplitude and phase responses of the pick-up equipment, the transmission medium, and the picture monitor, as well as on the size of the scanning spot.

Resolution (Vertical). The amount of resolvable detail in the vertical direction of a picture. It is usually expressed as the number of distinct horizontal lines (alternately black and white) which can be seen in a test pattern.

Vertical resolution is limited fundamentally by the number of horizontal scanning lines per frame. Beyond this, vertical resolution depends on the size and shape of the scanning spots and does not depend upon the high-frequency response or bandwidth of the transmission medium or picture monitor.

Ringing. An oscillatory transient occurring in the output of a system as a result of a sudden change in input. It is seen as alternate black and white lines, usually on the left side of a display, which gradually decay.

Scanning Line. A scanning line is made by the movement of the electron beam of an electron tube in a display device across a surface in a predetermined path or line, usually from left to right. This line appears as a narrow horizontal line having brightness.

Sensitivity. The signal current developed per unit incident light energy. Unless otherwise specified, the light energy is understood to be equivalent to that from an unfiltered incandescent source of 2870°K (tungsten); and its density, which is normally measured in watts per unit area, may then be expressed in footcandles.

Shading. A large section of brightness-gradient in the reproduced picture not present in the original scene.

Signal-to-Noise Ratio. The ratio of the value of the desired information to that of the noise (unwanted energy).

The ratio is usually expressed in terms of peak values (in the case of impulse noise) or in root-mean-square values (in the case of random noise) and is generally measured in decibels. However, when there is a possibility of ambiguity, suitable definitions of the signal and the noise should be included in the definition, as peak-signal to peak-noise ratio, root-mean-square signal to root-mean-square noise ratio, peak-to-peak signal to peak-to-peak noise ratio, etc.

The ratio is generally a function of the bandwidth of the transmission signal.

Signal-to-Noise Ratio (Camera Tubes). The ratio of peak-to-peak signal output current to root-mean-square noise in that output current.

Streaking. A term used to describe a picture condition in which objects appear to be extended horizontally beyond their normal boundaries. This condition is more apparent at the vertical edges of objects when there is a sudden transition as from black to white. The change in luminance is carried beyond the transition.

Synchronizing. Maintaining two or more scanning processes in phase.

Sync Signal. The signal employed to synchronize scanning. In television the signal is composed of pulses which occur at rates related to the line and field frequencies. The waveform specified by the U. S. Monochrome Standards is shown in Figure 12 of the "IRE Standards on Television: Methods of Testing Television Receivers", IRE, 1948.

The sync signal usually originates in a central sync generator and is added to the combination of picture signal and blanking signal (output signal from the pick-up equipment) to form the composite picture signal. In a television receiver the sync signal is normally separated from the picture signal and is used to synchronize the reflection circuity.

Target. A camera tube component having a surface which is scanned by an electron beam to generate a signal output current corresponding to the image pattern presented thereon.

Tearing. A term used to describe a picture condition in which groups of horizontal lines are displaced in an irregular manner.

Transients. Signals which endure for a brief time prior to the attainment of a steady-state condition. These may include overshoots, damped sinusoidal waves, etc.

Vertical Blanking. The portion of the blanking signal at the end of each field that suppresses display brightness during beam return from the bottom to the top of the raster.

Video. A term pertaining to the bandwidth and spectrum position of the signals resulting from television scanning of a camera tube or other pick-up device. In current usage "video" means a bandwidth in the order of megacycles and a spectrum position related to a zero cycles per second (direct current) signal.

Vidicon. A camera tube in which the image pattern is formed by photoconduction and is stored on that surface of the photoconductor which is scanned by an electron beam.

PHASE I

SECTION 1

INTRODUCTION

A major problem in simulated astronautical flight training is the generation of suitable images for training purposes. A previous study provided an extensive survey and analysis of existing image generation techniques and display methods (Buddenhagen and Wolpin, Reference 5). The conclusion drawn from this effort was that television systems appear to provide the best immediate solution to the problem, and hold greatest promise for future improvement.

This report describes a program which provided further insight into the problems of television display generation. A technique for complete display evaluation was developed, a survey of known methods of display generation is presented, and an existing projection system is evaluated. Conclusion of the program, Phase II of the overall effort, is the modification of this projector to provide a higher quality image than allowed in the original design.

SECTION 2

SCOPE OF EFFORT AND OBJECTIVES

PROGRAM REQUIREMENTS

The work performed on this project was undertaken to determine what specific problems are involved in generating a high quality, high brightness television display suitable for astronautical flight training applications. Apparatus for study was to be obtained from an existing F-151 Fixed Gunnery Trainer. Major areas for effort were as follows:

1. As a first step, it was necessary to remove the closed-circuit television (CCTV) system from the entire trainer. Since the trainer had been in storage for some time and was inoperable, maintenance and repair would be required to return the CCTV system to optimum condition.

2. Once the CCTV system was in operation, a technique for evaluating the projected display was to be developed. The new method must provide specific, quantitative data on system performance.

3. After a method for evaluation had been determined, the 7WP4 projection tube of the F-151 display device was to be evaluated with particular regard to use of this tube in higher resolution television systems. Should this tube prove unsuitable for the new application, a replacement tube is to be secured, and the projector modified to accommodate the different type of tube.

4. Certain high-gain screen materials were to be secured for use as a display surface in this study. These materials were to be mounted and prepared for use.

5. Upon completion of the above effort, the output system brightness transfer characteristics were to be established, and, if required, the projection system video amplitude linearity was to be modified to match the screen material characteristics. This would result in a linear ratio in output brightness referred to input video signal level.

6. The final requirement was to convert the F-151 projector from 525-line operation to a 1029-line television system format.

SUMMARY OF PROGRAM ACCOMPLISHMENTS

Effort was applied to the program in the same order as outlined previously, and therefore is summarized accordingly:

1. The initial condition of the F-151 trainer was not good. This resulted in the seemingly simple operation of separating the CCTV devices from the F-151 trainer becoming an extensive effort. Considerable time was spent rewiring, adjusting, calibrating, and trouble-shooting the CCTV equipment. In some instances repair became economically impractical, and substitutions of new, industrial equipment were in order:

a. The direct view monitor in the F-151 CCTV system required complete overhaul. A new industrial monitor was obtained more reasonably and performance of the new device exceeded the specifications of the F-151 unit.

b. The F-151 CCTV synchronizing generator could not be repaired after considerable investigation into the cause of intermittent malfunction. In addition the F-151 video circuitry appeared degraded. Therefore a new, high resolution industrial camera system was obtained. This resulted in a stable synchronizing reference as well as an 800-line resolution capability, as opposed to the 450-line optimum F-151 performance.

2. A successful evaluation technique, one which advances the state of the art in evaluation of television displays, was developed. A detailed explanation is presented in Section 4. The new technique gives a quantitative measure, for any specified format, of:

a. Resolution

b. Contrast Ratio

c. Brightness

3. The technique developed for image evaluation was used to analyze performance of the 7WP4 projection tube as used in a 525-line television as well as predict the suitability of the 7WP4 in a 1029-line system application. The consideration is fully described in Section 5, and detailed calculations are presented in the Appendices. Survey of the projection tube manufacturers revealed that the 7WP4 is a unique device; no suitable equal or superior replacement could be located. Therefore tube replacement did not become a project consideration.

4. The specific screen materials specified for procurement in this contract became available to the government through another source. Rather than duplicate this, alternate materials were procured and mounted. An analysis of these materials was performed by government personnel.

5. Previous efforts indicated that display quality and brightness were limited by the 7WP4 cathode-ray tube. Since no improved devices were available, further measurement, such as transfer characteristics, were not appropriate. The general brightness outputs were tabulated, but no further correlation was in order.

6. The final project objective, converting the television projector from 525-line system operation to 1029-line capability, is described in detail in Phase II of this report. This program required the following effort:

a. Development of a new horizontal deflection circuit operating at 30.87 kc rather than the 15.75 kc rate used in 525-line systems.

b. Fabrication of a new vertical deflection circuit.

c. Development of a 20 mc bandwidth video amplifier capable of driving the 7WP4 projection tube.

d. The above units, plus appropriate control devices, were assembled into cabinetry and interconnected into the F-151 CCTV system.

The purpose of this conversion is to provide a mechanism for analysis of large area displays at the present limit of CCTV state of the art.

SECTION 3

SURVEY OF DISPLAY DEVICES AND DISPLAY SURFACES

INTRODUCTION

The point of utilization in a television system is the display surface. Thus the display device is the focal point of the operation to the observer. Generally speaking, the display devices perform an electrical-to-light conversion; the electronic television signal, representing the scene viewed by the camera, is converted to patterns of contrast in the display surface brightness.

Displays provided for flight simulation training have different requirements from those generated by the theater projectionist who presents an image to a large audience distributed over a fairly wide area and seated in a darkened environment. The training material is presented to a very few persons who are confined in a comparatively small area, and the ambient environment cannot be darkened below certain reasonable levels. Moreover, to realistically simulate the sun and other space conditions, very high brightness displays must be used. The greatest problem is the generation of realistic presence and depth perception which must be maintained throughout the simulated tumble, pitch, roll and yaw of the piloted vehicle.

To approach a solution to this and the associated problems, the entire state of the art of television and projection techniques was reviewed. The possibilities of direct and indirect view displays were canvassed; the most recent innovations in large area display devices were investigated; and the question of improving the display surface, a large area projection screen, was considered.

DIRECT VIEW DISPLAY DEVICES

Direct display devices, for example the familiar entertainment television receivers, employ a luminous material in the observer's visual field. This phosphor is excited to varying levels of brightness by an electron beam which is controlled by an electronic signal. Proper patterns of brightness and contrast are developed when the beam scans the luminous material in a predetermined pattern. These principles are all embodied in a cathode-ray tube, the only direct display device in common use at the present time.

The cathode-ray tube is an evacuated envelope usually constructed of glass and containing the necessary elements to generate the required image in the manner described above (see Figure 1). It is an efficient device because the transparent faceplate is the only light attenuating element lying between the phosphor light source and the viewer. It is also highly sophisticated; over the years many techniques have been devised to improve performance and efficiency, and the electron beam has been accelerated to high velocity to generate very bright displays, averaging approximately 30 foot-lamberts. The major limitation of the cathode-ray tube is the practical size of the envelope; tubes as large as 23 inches in diameter with approximately 150 square inches of viewing surface are available. These also have considerable depth since narrow deflection angles are required to preserve best focus, geometry, etc. The equipment format generally used requires a large volume for tube mounting; the minimum depth for any size screen is approximately 12 inches, except in the case of fairly low performance entertainment tubes.

INDIRECT VIEW DISPLAYS

The various methods of indirect display generation currently in use all require the projection of a prepared image onto a passive, reflective display surface, for example, motion picture displays. Indirect display equipment probably has received less emphasis and has thus shown less technical improvement than other television system components. The present devices apparently satisfy the larger segment of demand. General requirements are for commercial applications that present suitable images, in terms of resolution and brightness, which cover relatively small areas and are used in environments of subdued ambient lighting. There has been interest in large area, high brightness displays with improved resolution, but unfortunately this interest is not sufficiently intense to justify large development programs to perfect such devices. Therefore such items exhibit limited performance, must be obtained on a special order basis, and are quite expensive.

With such television projection a large image, as much as 15 by 20 feet, can be obtained. These large area displays are required for most commercial applications, as in theaters. The major problem then is brightness, as an image perhaps 3.75 by 5 inches at the source would have to be magnified 2300 times to attain 15 by 20 feet (300

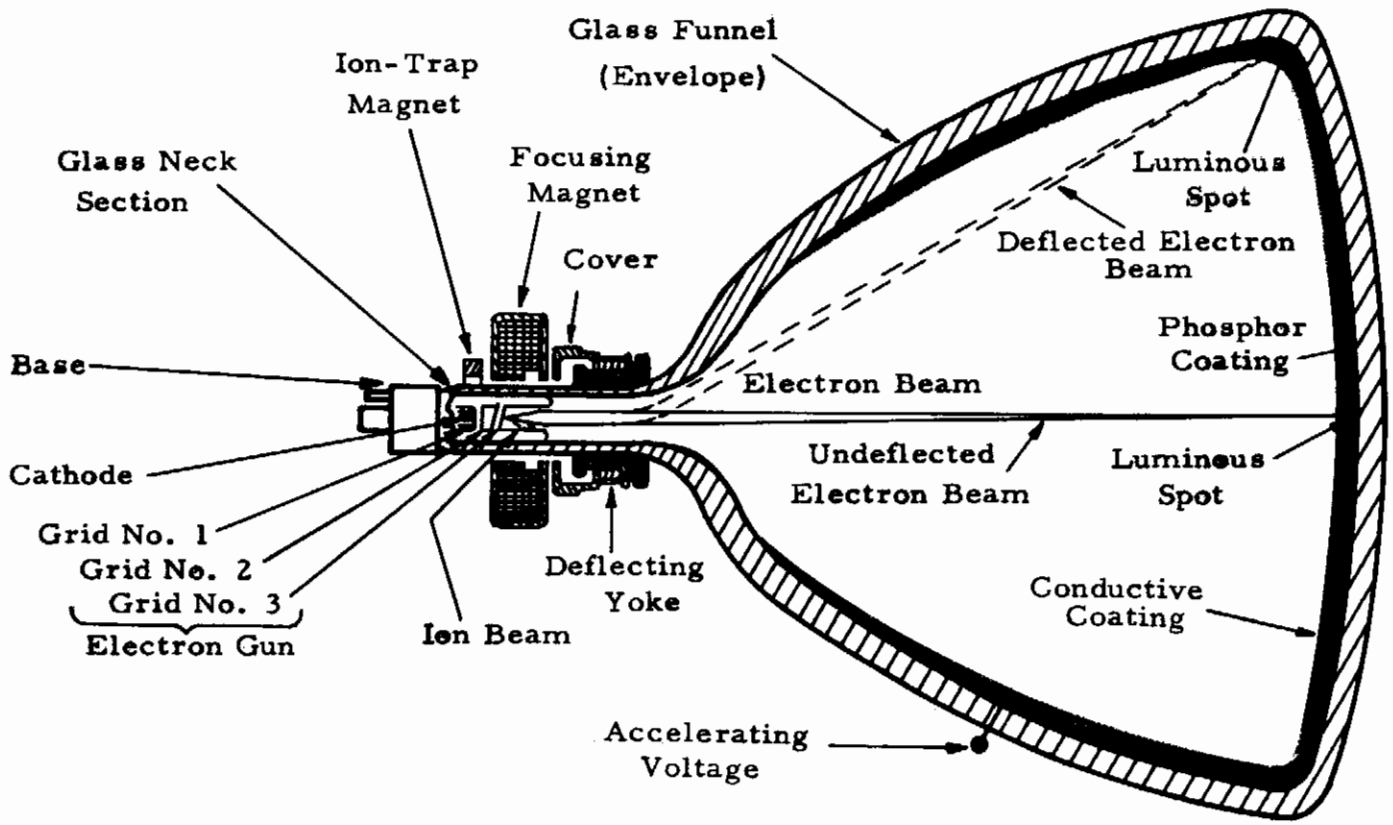


Figure 1. **Typical Cathode-Ray Tube**

square feet) at the screen. Obviously the source must be intense to provide a suitably bright display of such size, especially since intensity at a display surface is a function of the square of the distance from the effective point source.

Suppose that a source 3.75 by 5 inches is to be projected as an image of 15 by 20 feet as shown in Figure 2, representing the typical theater arrangement. The source brightness required to provide a 30 foot-lambert incident display surface brightness can then be calculated. If it is desired to locate the source 80 feet from the display surface, that is,

$$d = 80 \text{ feet, therefore } \tan \theta = \frac{15/2}{80 + r_1}$$

(but r_1 is very small and may be considered negligible);
thus,

$$\tan \theta = \frac{7.5}{80} = 0.094, \text{ and } \theta = 5.4 \text{ degrees.}$$

The distance r_1 may now be calculated:

$$\tan \theta = \frac{3.75 \text{ in.}/2}{r_1} \quad \text{or } r_1 = \frac{1.875}{0.094} \text{ inches}$$

$$r_1 = 20 \text{ inches} = 1.67 \text{ feet}$$

$$r_2 = 80 + 1.67 \text{ feet} = 81.67 \text{ feet, as shown in Figure 2.}$$

For a 30 foot-lambert display brightness at this distance, the equivalent point source intensity must be calculated:

specified screen surface brightness = 30 foot-lamberts

$$\text{foot-lambert} = \frac{1}{\pi} \text{ (candles/sq. ft.)}$$

$$\therefore\ 30 \text{ foot-lamberts} = \frac{30}{\pi} \text{ candles/sq. ft.}$$

$$\therefore\ B = \frac{30}{\pi} \text{ candles/sq. ft.}$$

$$E = \frac{F}{A} = \pi B \qquad \text{where} \qquad \begin{array}{l} E = \text{luminance} \\ F = \text{light intensity} \\ B = \text{light flux} \end{array}$$

$$E = \pi B = \frac{\pi \times 30}{\pi} = 30 \text{ lumens/ sq. ft.}$$

$$\therefore\ I = Er_2^2 = \frac{30 \text{ lumens}}{\text{ft}^2} \times (81.67)^2 \text{ ft}^2 = 200,000 \text{ lumens}$$

$$E = \frac{I}{r_1^2} = \frac{200,000 \text{ lumens}}{(1.67)^2 \text{ ft}^2} = 71.5 \times 10^3 \text{ lumens/ft}^2$$

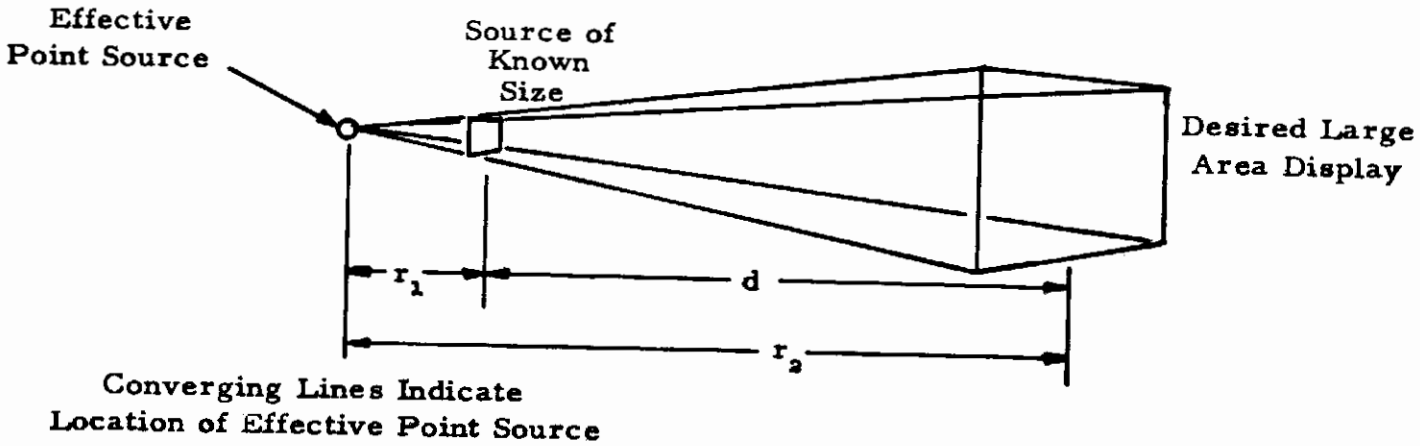
$$B = \frac{E}{\pi} = \frac{71.5 \times 10^3}{\pi} \text{ candles/ft}^2$$

$$\pi \text{ foot-lamberts} = \text{candle/ ft}^2$$

$$\therefore\ \frac{71.5 \times 10^3}{\pi} \times \pi \text{ foot-lamberts} = \frac{71.5 \times 10^3}{\pi} \text{ candle/ft}^2$$

The actual source brightness for this sample case must be,

$$B = 71.5 \times 10^3 \text{ foot-lamberts}$$



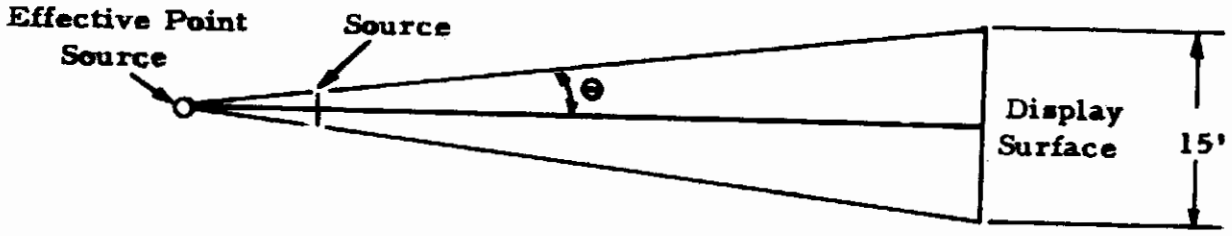


Figure 2. Simplified Relationship of Large Area Indirect Display to Source

It is evident that a very bright source must be provided for such a display; indeed, this level is beyond the present state of the art. Note also that even this figure is optimistic since it represents the level of projected intensity, and projection devices employ optics and other image processing devices having low efficiency. It is thus reasonable to assume that a source of 18.8 square inches must have a brightness of at least 150,000 foot-lamberts to produce a 15 by 20 foot display having a 30 foot-lambert intensity.

Obviously, large area displays of this type in an illuminated room or an open daylight area are not practical since even the brightest projection sources in use at the present time provide an output of only 1600 lumens (for an 18.8 square inch source size, this would be 12,300 foot-lamberts which would provide only 5.2 foot-lamberts of 15 by 20 foot display brightness). It is evident that indirect view displays require a subdued ambient or, preferably, a completely darkened viewing room to present information to a large audience.

Such commercial applications have dictated the emphasis on equipment development and product improvement, but requirements in flight simulation are quite different. The long projection distances and very large area displays are not required; a projected 6 by 8 foot image will fulfill many requirements. The viewer will be confined to a small viewing area, which allows the use of more directive, higher gain screens rather than the beaded screens required to serve a large audience. Therefore the survey indicates that the commercial equipment is not directly suited to flight simulation use, and a great area of possible equipment improvement exists.

LARGE AREA INDIRECT DISPLAY DEVICES

A variety of indirect display devices has been devised for the accomplishment of large area displays. These may be categorized generally as refractive optics systems, reflective optics systems, and light modulating systems.

REFRACTIVE OPTICS SYSTEMS

The simplest system is the "refractive optics" system, in essence, a very high intensity cathode-ray tube with an optical system which directs the light over the desired distance to a viewing screen. Unfortunately the refractive optics system is very

inefficient when used with practical optical components. As shown in Figure 3, only a small portion of the light radiating from a point on the phosphor is presented to the optical system because of the 180-degree radiation from the tube phosphor and the resultant scattering of the emitted light. Efficiencies of 10 to 15 percent, for example, are claimed for present apparatus. Elaborate attention to tube design and detailed consideration of the application in respect to such matters as proper cooling and x-ray protection have yielded tube outputs as high as 30,000 foot-lamberts which result in an output of perhaps 300 foot-lamberts from present-day projection equipment.

The major advantage of the refractive optics system is its relative simplicity; beside the cathode-ray tube, the optical elements, and the screen, only a housing with proper voltages and cooling equipment for the cathode-ray tube are required. Thus the refractive optics system is much less complex than other types of projection systems. In addition, a high resolution display is theoretically possible; the cathode-ray tube itself is the limiting item if care is taken with the optical design of the lens system.

Note that it is possible to obtain fairly bright display from a refractive system if the lens diameter equals or exceeds the cathode-ray tube diameter, thus raising the efficiency of light collection. Limitations are then imposed by optical design. A large lens, 7 inches in diameter or greater, is difficult to produce while maintaining high resolution performance. Such precise optical elements are generally considered prohibitively expensive, probably falling between $8,000 to $10,000.

The disadvantages of the refractive optics system include the poor efficiency of light utilization (already discussed) and the large amount of support equipment required in the case of a very high intensity cathode-ray tube.

At high brightness levels, an elaborate cooling technique and interlock system must be provided to prevent cathode-ray tube damage since as much as 160 watts may be present in a small screen area at an 80-kilovolt level. Also severe thermal stress may cause envelope glass breakage and resultant implosion of the tube structure. The phosphor screen of cathode-ray tubes may be literally burned off if the undeflected beam dwells on a spot of phosphor for even a few microseconds. In addition, complete x-ray protection must

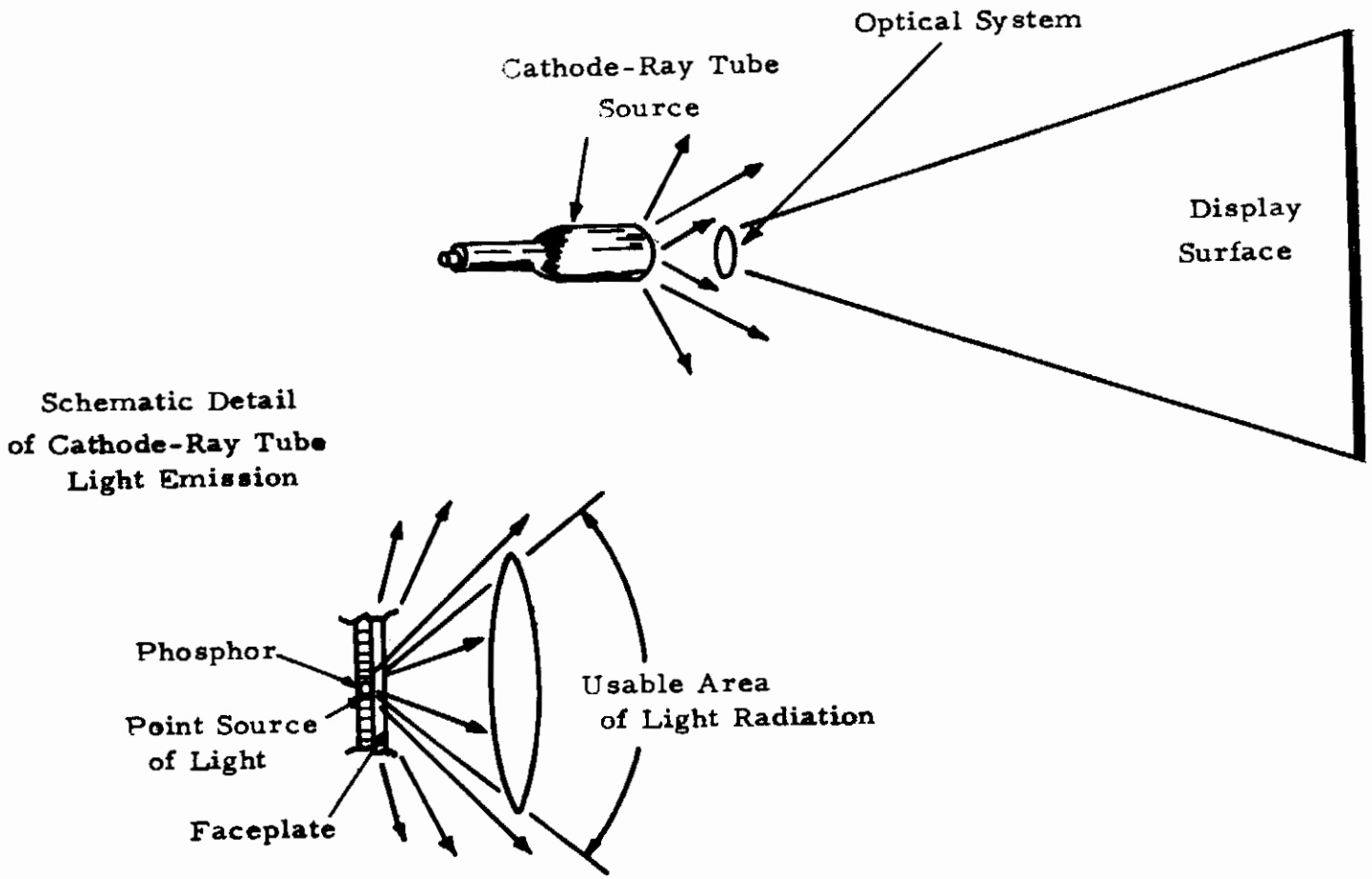


Figure 3. Schematic of a Refractive Optics Projection System

be provided whenever voltages in excess of 25 kilovolts are used. Projection tube faceplate browning also occurs as a result of radiation level when high voltage acceleration (to 80 kilovolts) is used. Moreover, to prevent arc-over at 50 kilovolts or above, the cooling air for the tube must be clean and free of even microscopic particles. Because of these difficulties, refractive optics systems with high brightness levels of the type discussed are not mass-produced and must be specially ordered. The cost is estimated at $10,000 per unit minimum.

REFLECTIVE OPTICS SYSTEMS

A more efficient projection method, which also employs a cathode-ray tube, is the reflective optics system commonly referred to as the Schmidt system. The Schmidt system exhibits an advantage over the refractive optics system in that a much greater percentage of cathode-ray tube light output is utilized. As shown in Figure 4 emitted light is captured by the spherical mirror. This output is then reflected to the display surface through appropriate correction optics. The result is a considerable improvement in brightness output, and the required equipment is usually more compact because the light is "folded over" by the reflective process, reducing length. Generally speaking, smaller projection tubes with lower accelerating voltages can be used because more of the cathode-ray tube output is utilized. However, note that even with this improvement, a relatively low brightness display results in theater projection because of the great degree of image magnification required and the limited output available from the cathode-ray tube. A display brightness of 10 foot-lamberts -- the equivalent of the average motion picture display -- is a reasonable expectation.

The improved performance of the reflective optics system is not achieved without attendant disadvantages. A major consideration is the fact that the reflective and corrective lens must be precise, and such parts are expensive to produce. Even so, the resolution and uniformity of the focus of the display are usually less than those of other systems because of the aberrations in these parts which occur despite precision production. Another major problem is the correct design of the lens to compensate for the varying focal distances from the spot source to the reflecting mirror and correcting lens (see distances labeled f_1, f_2, and f_3 in Figure 4). Also, once

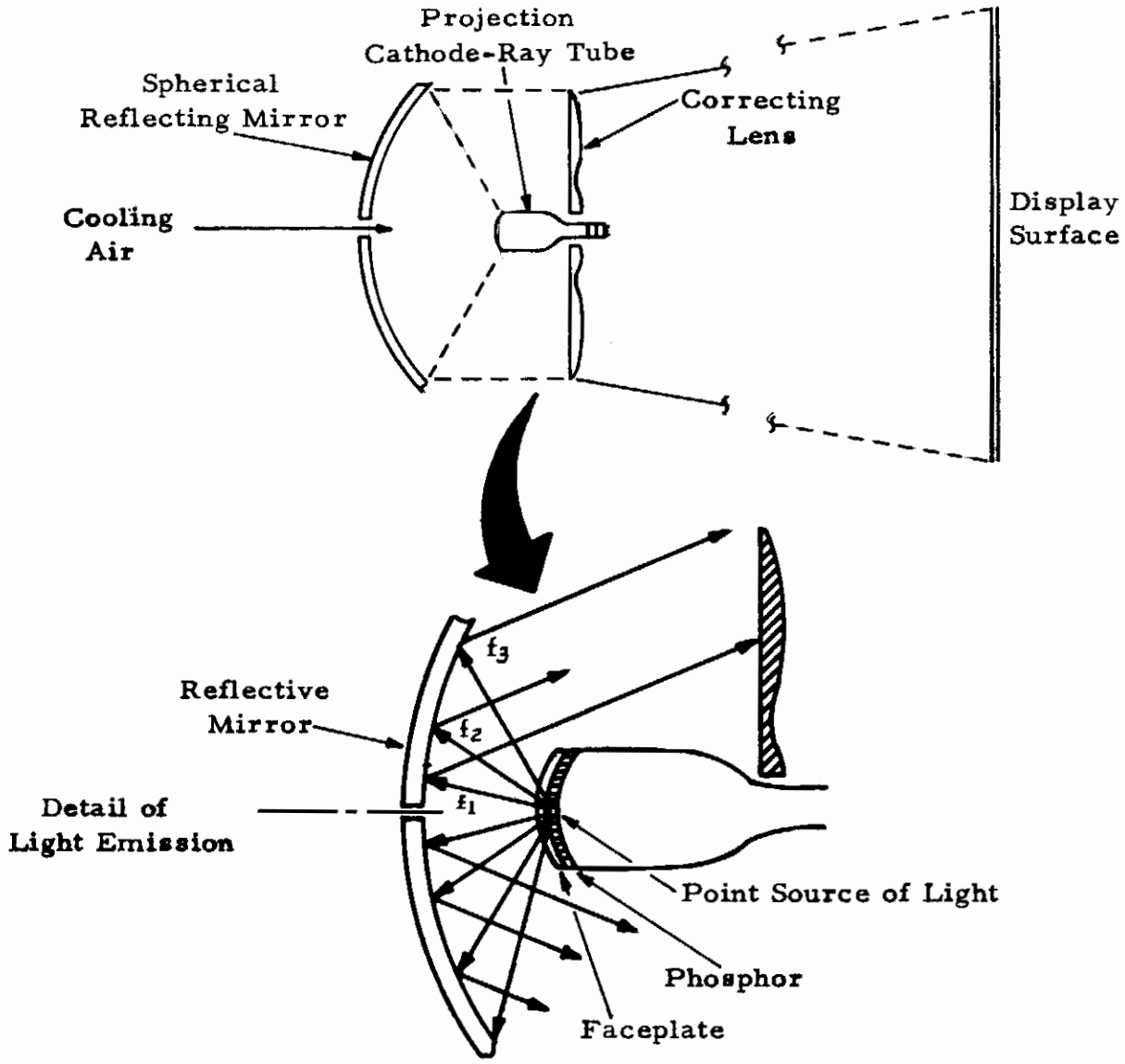


Figure 4. . **Schematic of a Reflective Optics Projection System**

again, cooling air must be provided to the cathode-ray tube face to prevent excessive thermal stress which may result in tube implosion. The danger of cathode-ray tube screen destruction from an undeflected beam is also present. To prevent such occurrences, the system must be interlocked.

Displays making use of reflective optics systems of a quality suitable for broadcast and for educational use have been demonstrated (approximately 350 lines), but to date no high resolution devices of this type have appeared. Mass-produced Schmidt projectors of the lower quality described can be obtained for approximately $2500.

LIGHT MODULATION SYSTEMS

A more successful method of generating high brightness, large area displays than either the refractive optics or reflective optics systems is the light modulation system. In this arrangement, a continuous light beam from an independent source is modulated. Xenon lamps in the 3-kilowatt range have been employed to project intensities of as much as 1600 lumens. However, the modulation process is quite elaborate (see Figure 5) and has not as yet been perfected to the point of universal acceptance.

The operation of the system may be explained as follows: In the case of no electron beam emission, the oil film deposited on a surface is very smooth. The light beam directed to this film from the source via the primary mirror at an angle of incidence (θ_1) is reflected from the smooth oil surface at an angle of reflection (θ_2) equal to the angle of incidence. The reflected light beam then travels to a grating bar (pattern of slits) where it is blocked (in the no electron beam case). Thus no light energy passes to the secondary mirror and projection lens, and the viewing surface remains dark.

In the case of electron beam emission, the oil surface is deformed by the striking of the electron beam. Then the light beam may not impinge on the oil surface in the horizontal plane(see Figure 5) but instead on a reference plane of α. Thus the angle of incidence is $\alpha + \theta_1$ and the angle of reflection, which always equals the angle of incidence, will be $\theta_2 + \alpha$ as shown. When this occurs, the reflected light beam is passed through a slit in the grating bar and presents brightness to the display surface via the secondary

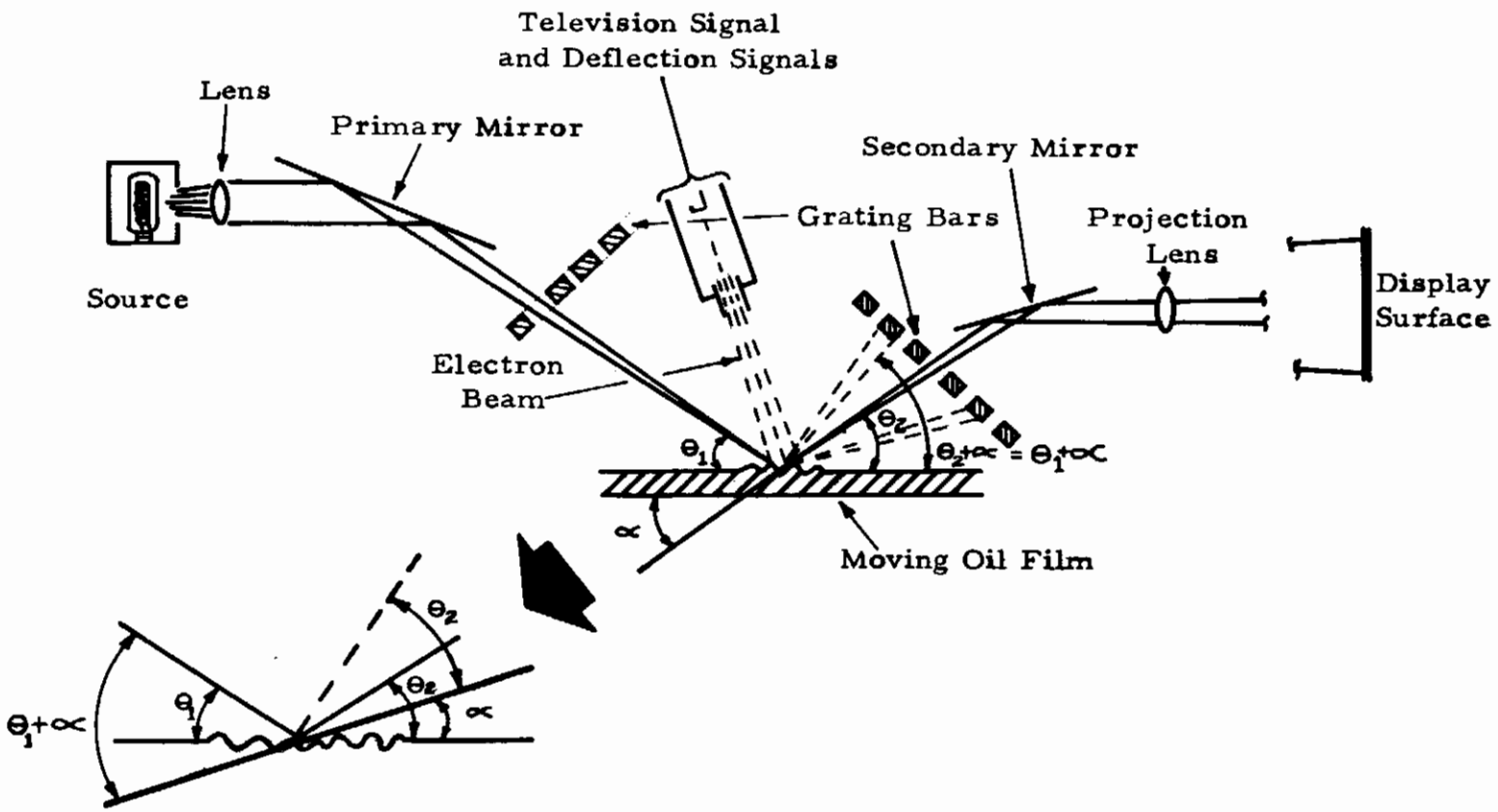


Figure 5. Schematic Diagram of Light Beam Modulation Projection System Principle

mirror and projection lens. This continuing process modulates the beam of light and thereby generates the proper brightness contrast pattern on the display surface.

The mechanism described is a precision device of considerable size. Since the cathode and electron beam must be contained in a vacuum, the entire assembly, including electron gun, deflection plates, oil film transport, etc., must also be located in a vacuum chamber equipped with transparent ports to allow the passage of the light beam. Manufacturers have not published detailed descriptions of the design problems involved, but certain difficulties are known to exist:

1. Oil properties and oil handling procedures present very serious design problems. Ordinary oils "outgas" in a vacuum, releasing oil particles and destroying the purity of the vacuum. Also the oil changes state as it is bombarded by the electron beam. The resulting "dirty" oil does not have the proper deformation properties. A special oil that does not outgas severely must be used, and this fluid must be constantly replenished to prevent degradation. Thus the oil must be passed into and out of the vacuum in a continuous stream,or continuous processing must be provided within the vacuum.

2. The slightest degradation of the vacuum results in a short life for the electron gun since impurities speed oxidation of the cathode heater elements and cause rapid burnout. The most successful arrangment known to date is a rotating turret of seven electron guns; when one burns out, another is rotated into position without upsetting the system vacuum. Under ideal conditions, as much as 200 hours of operation may be obtained with this turret arrangement. Then the system vacuum must be released, and the projector must be entered to effect gun replacement. This amounts to minor overhaul as the oil must also be changed at about the same time. The system would be out of operation a matter of hours.

3. The apparatus required necessarily results in a large assembly. Projector and power supply cabinets may occupy over 60 cubic feet and weigh over 1350 pounds. Power consumption, including the high intensity light sources, can approach 6 kilowatts. The system output, as energy, is very low even though it is of high light intensity. Thus external ventilation or air conditioning is required to remove the 6 kilowatt input as heat output in order to

maintain the equipment at temperatures within operating limits.

4. The oil transportation dictates that the device be used on one plane only; the projector cannot be tilted or rotated during operation since vibration or acceleration will affect the smoothness of the oil film. Thus a secure, rigid mount must be provided.

Despite these problems and the attendant disadvantages, light modulation systems have a number of unique advantages for large area displays: the equipment provides the highest resolution (displays of 1029-lines have been readily obtained) and the brightest (relative to other projection methods) large area displays available at the present time. Also, the light source, which is independent of the modulation devices (as opposed to the interaction of features in the conventional cathode-ray tube) can be exchanged, replaced, and/or updated at any time without upsetting the modulation process.

SUMMARY

Light beam modulation methods are represented as holding the greatest promise for future improvement of large area displays though the elaborate operating technique required, the price (in excess of $50,000), the size, weight, and lack of flexibility of operation are limiting. All current industrial effort appears to be oriented to light modulation devices because cathode-ray tubes, the major constituent of all other devices, both direct and indirect, present technical problems of long standing, and sufficient commercial demand does not appear to exist to support major improvement programs or developmental efforts. Two manufacturers now offer light modulation devices under the trade names of "Eidophor" and "Light Valve" projectors. It does not appear that proper consideration is being given to flight simulation applications by industrial groups. The cost, physical size, and lack of ability to operate under acceleration makes the light valve devices unsuitable for simulator applications. A small, inexpensive, rugged device, such as a cathode ray tube, is desirable for simulator applications, assuming such a device can be built to provide adequate contrast, resolution and brightness.

DISPLAY SURFACES

No peripheral equipment is required in direct display devices since the observer views the image on the same plane on which it is generated. This is not true in the case of indirect display devices;

a screen, frosted glass, wall, sheet, or other such surface must be provided to permit satisfactory image formation of the desired size, shape, and format. This display surface is generally termed a "screen". Whether it is constructed of glass, fabric, painted structural material, or a metal film, the problems attendant upon its construction are basically the same.

A screen is a passive device, that is, it cannot perform any operation on the image; it can only display the information presented to it. Older and more ordinary screens have a diffusing reflective surface (see Figure 6), and the light may be reflected in any direction, at random, depending on the screen's surface characteristics in small areas. The observer, at any one point, can intercept only a small fraction of the reflected light with his field of vision. The reflected energy is distributed over a wide angle, θ , generally referred to as the exit pupil, and therefore an audience which is comparatively wide-spread can observe the image equally well from any position within the exit pupil. Ordinary screens, glass beaded or flat white, may have as much as a 90-degree exit pupil.

Screen Characteristics

Obviously both the exit pupil and the reflectivity of a screen must be specified to completely describe the characteristics of a screen. Within the industry the matte-white surface, especially one formed by a deposited layer of magnesium oxide, is considered a nearly perfect diffusing reflective surface and is used, informally, as the standard. Comparisons of screens and screen materials are thus based on measurements made using the matte-white screen as the reference. The "screen gain" is derived as shown in the following sample problem:

measured reflected light from matte-white surface
= 15 foot-lamberts

measured reflected light from surface under test
= 30 foot-lamberts

In this particular case, for example, the gain of the screen under test is 30/15 = 2. (The matte-white screen gain is always unity.)

A complete testing procedure used by one leading manufacturer (ref. 7) is described:

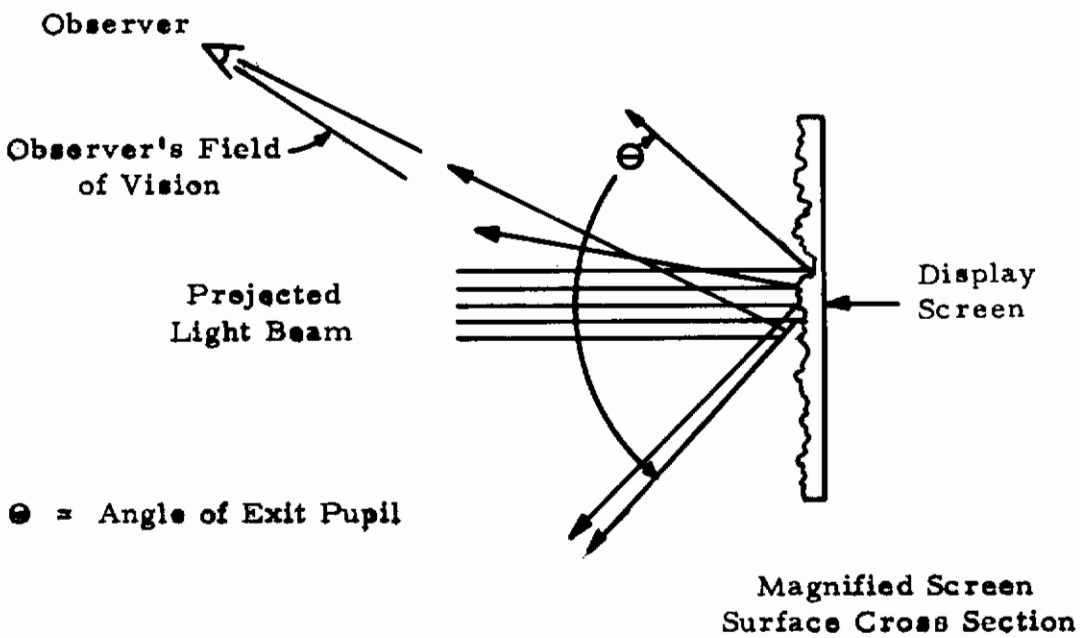
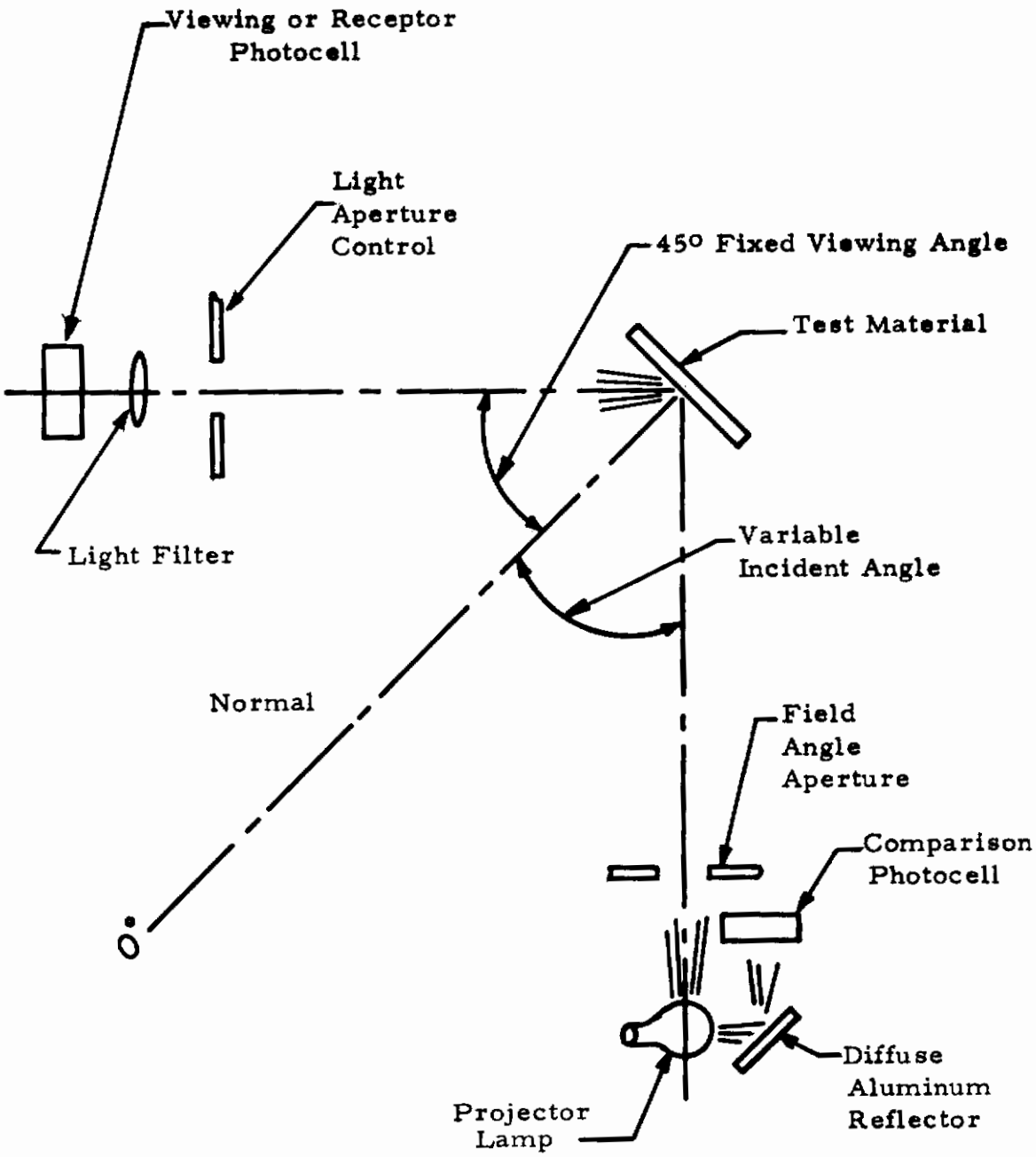


Figure 6. Diffusing Reflective Screen Operation

"The evaluation of reflectance was made by means of the Gardner Photometric Unit and Goniophotometer. The arrangement of the elements in the Goniophotometer is shown below:



"The operation of this equipment is based upon comparing the output current of a viewing or receptor photocell with a constant current output of a comparison photocell. The comparison photocell current is established by the adjustment of a diffuse aluminum reflector which reflects a portion of the light from the projection lamp into the comparison photocell.

"The projected light from the lamp passes through a field angle adjustment aperture and impinges upon the surface of the specimen being evaluated. The incident light is reflected from the specimen and passes through a light controlling aperture into the receptor photocell. The light into the receptor cell is further modified by the insertion of a green, amber, or blue filter in front of the cell.

"The value of reflectance of a surface being evaluated is indicated on a graduated dial on the Photometric unit. This dial is servo-motor-rotated by an amount proportional to the difference in current output between the standard comparison photocell and the receptor photocell.

"In the Goniophotometer the receptor photocell is in a permanently fixed position. The surface being evaluated for reflectance is fixed at a predetermined angle with respect to the receptor photocell. The projection light is rotated about the surface being tested to vary the angle of incident light to produce a polar plot of reflectance.

"The Photometric unit and Goniophotometer were calibrated by using a white porcelain ceramic tile standard with known values of reflectance versus angle of incident light for a 45° viewing angle. In making the calibration the following parameters were established:

1. The angle of view was set at 45 degrees.

2. The green filter was placed in front of the receptor cell.

3. The light controlling aperture for the receptor cell was set at 100. This aperture is variable by factors of 10 which

give a multiplying factor to the dial indicator of the Photometric unit of 0.1, 1, 10, and 100.

4. The field angle aperture in front of the projection lamp was set at 4.

5. The projection lamp was rotated so the incident light was 45 degrees off normal and the reflection of light into the receptor cell was maximum.

6. The diffuse aluminum reflector beneath the projection lamp was adjusted to produce an unbalance current between the two photocells to give a dial indication of 1.34. This established the calibration.

"To obtain the most accurate values of reflectance for different screen materials as compared to the standard, all the parameters with exception of the receptor cell aperture were maintained at their calibration settings. By this procedure the reflectance of a material under test was simply the dial indication multiplied by the receptor cell aperture for all angles of incident light. The receptor cell aperture was either 100 which was the calibration setting or the value of 10. The equation below was applicable to the standard as well as the different types of screen material.

$$r_{\text{(Reflectance of Specimen)}} = S_{\text{(Dial Indication)}} \times f_{\text{(Receptor Cell Aperture)}}"$$

Avenues of Improvement

Since a screen is a passive device incapable of image processing, not many avenues of improvement can be pursued. However, the application will govern the material selected and thus both the brightness and the exit pupil.

It is assumed that all screens are 100-percent efficient, that is, that all light incident on a screen surface is reflected from the screen. Then a negligible amount, if any, of the light can be absorbed as heat or other energy. Also, it has been shown that incident light is reflected over some angle of exit pupil. Obviously, the larger the exit pupil, the less brightness is reflected to any one point within

the pupil since the total reflected light is a constant, that is,

$$\theta \quad I_R = K$$

where

θ = exit pupil, degrees

I_R = reflected light intensity at any small point in the exit pupil

It is further assumed that reflectivity is uniform throughout the exit pupil. This is not exact since the actual (practical) material does present reflectance, as shown in Figure 7. However, it is felt that the error resulting from the analysis based on ideal reflectance properties is negligible.

The design approach to screen improvement then involves obtaining precise control over the exit pupil in screen manufacture. Various materials have been used, beaded glass, lenticular films, silver, aluminum lacquer, metalized vinyl, etc., and gains of as much as 40 have been measured; "retro-reflectors" exhibit gains higher than this, possibly to 200. However, the exit pupil may also be reduced to as little as 10 degrees or less. Of course, a mirror represents the extreme end of the high brightness, very directional, reflecting material range. All other materials fall between the range established by the mirror (a high intensity, narrow exit pupil device with a gain of approximately 1000 and a θ of approximately 2 degrees) and the diffusing matte white (a low intensity, wide exit pupil device with a gain of 1.0 and a θ of more than 90 degrees). A compromise selection must therefore be made from this range to suit the intended application.

VIEWING PROBLEMS

In view of the state of the art just described, the following possible approaches were given consideration as a means of supplying adequate displays for flight simulation training:

1. The use of a small area direct view display at simulated observation ports and windows.

2. The use of small area projection with the projectors affixed to the space craft so as to project an image to screens placed in the

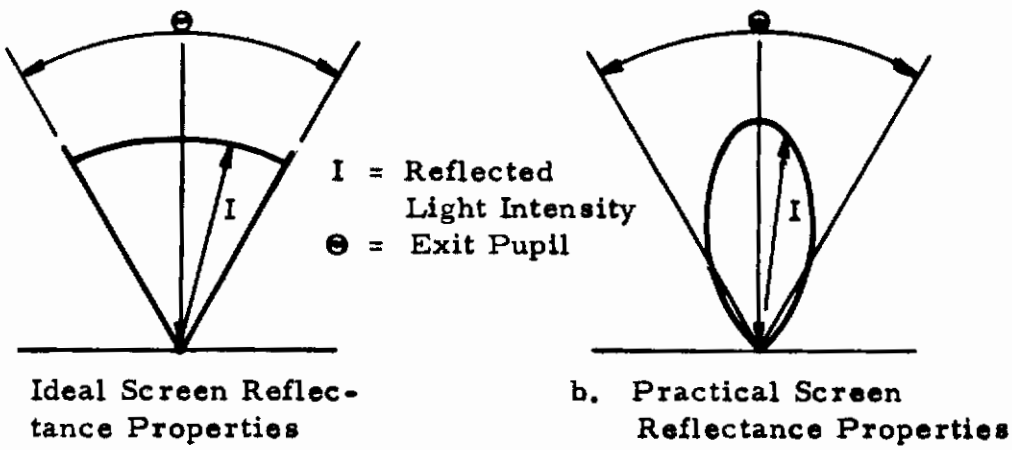


Figure 7. **Screen Reflectance Properties**

field of view of the craft's observation ports and windows.

3. The use of small area direct view displays affixed to the space craft but used with other devices to produce a satisfactory display.

4. The use of a very large area display to generate a complete background which would surround the "piloted" craft at a distance sufficient to create the proper depth of field. The ideal display would be a complete sphere of image surrounding the craft.

The first method, mounting a direct view television monitor in a simulated window or port, is that commonly used in airplane pilot training devices. It is not entirely satisfactory because the image does not appear at a distance (the plane of focus is not at infinity), and the raster scanning lines detract from realism. This type of display was therefore not considered further.

The second alternative would require projection devices affixed to the vehicle if the displays were to be projected in synchronism with the motion of the moving, piloted vehicle. Since these devices are quite large and heavy and the brighter beam modulation devices are inflexible as to orientation, this approach was not considered further. However, the general data obtained concerning methods of generating a projected, indirectly viewed image may be applicable for future considerations.

The third approach suggests the use of small area direct view displays with peripheral equipment. A study was therefore undertaken by personnel of Wright-Patterson Air Force Base to evaluate a virtual image device using a direct view display of a closed circuit television system. An arrangement was devised (see Figure 8) which provides an image whose plane of focus appears at infinity, even though the display is located a short distance away. The demonstrations were quite impressive; the image is very realistic. An observer had a definite "feel" for the depth of the scene and relative location of the objects appearing in the viewing port. The arrangement would be adaptable to almost all forms of display. In the particular simulation requirements under consideration, this method allows the generation of a virtual image whose apparent plane of focus is at infinity, while taking advantage of the brightness and resolution available in direct view displays. This may offer a means of providing color displays in advance of color-capable, large

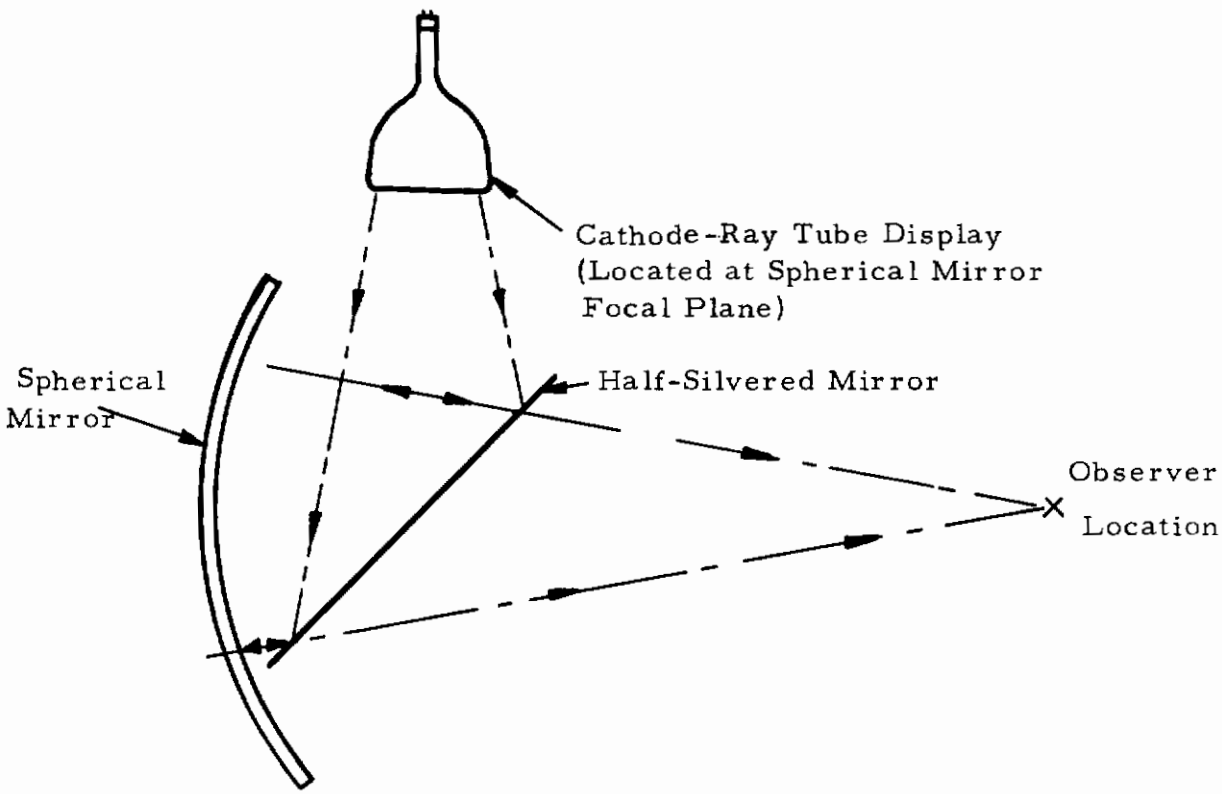


Figure 8. Virtual Image Viewing Arrangement

area, projection displays. This method provides a viewing angle of 90° or more for an observer confined to a limited area, as in space flight simulation.

The fourth approach was that given the greatest consideration in the present study. An attempt was made to generate large scale displays which would provide a complete background image for a simulated space vehicle similar to the conventional projection simulator of the F-151 Fixed Gunnery Trainer described in WADC Technical Report 58-141 (see Reference 4, page 83). That system display is composed of a refractive optics projector which uses a cathode-ray tube as an image source. The initial display equipment included only the refractive optics projector and a diffusing screen that was a segment of a sphere. The result, as predicted in a previous section, was a low brightness image that could be observed over a wide exit pupil angle. Since the cathode-ray tube source was presenting the brightest image attainable with present-day tubes, the display surface and the viewing arrangment and conditions were the possible areas of improvement.

As noted previously, improved reflective screen brightness can be achieved by narrowing the exit pupil angle through design of the screen surface. However, as shown in Figures 7 and 9, screens made of the high-gain materials present a very directive reflected pattern, and the observer must sit within the source to view the bright image, a physical impossibility. A compromise location places the subject close to the projection lens. Reasonable brightness might be achieved at such a spot, but the limitations on observer movement are obvious, and there is also the matter of personnel safety to be considered at a location near the cathode-ray tube in respect to x-ray radiation and possible tube implosion.

A series of experiments proved the feasibility of a mirror arrangement for viewing large displays when highest gain screens are employed. A half-silvered mirror was inserted into the projection path to provide the arrangement shown in Figure 10. The advantage of the arrangment is the relative freedom of the observer's position.

The light from the projector is directed to the half-silvered mirror, that is, to a mirror that will reflect half the light and will transmit half the light. In this case the reflected portion of the image is not utilized, but half of it is passed through the mirror onto the screen. The light intensity is reflected from the screen in a

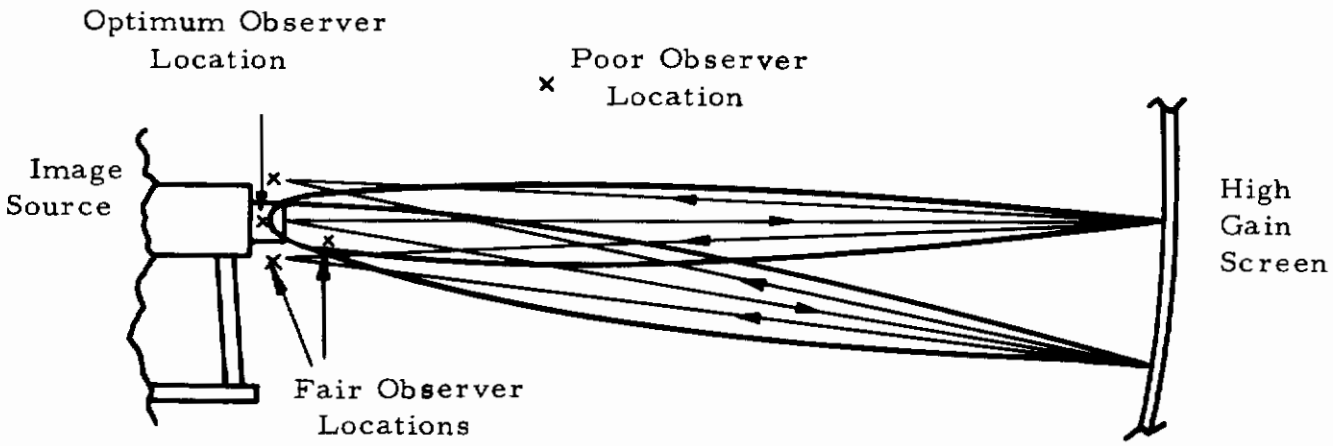


Figure 9. Schematic of Projector - High Gain Screen Layout Showing Possible Viewing Locations

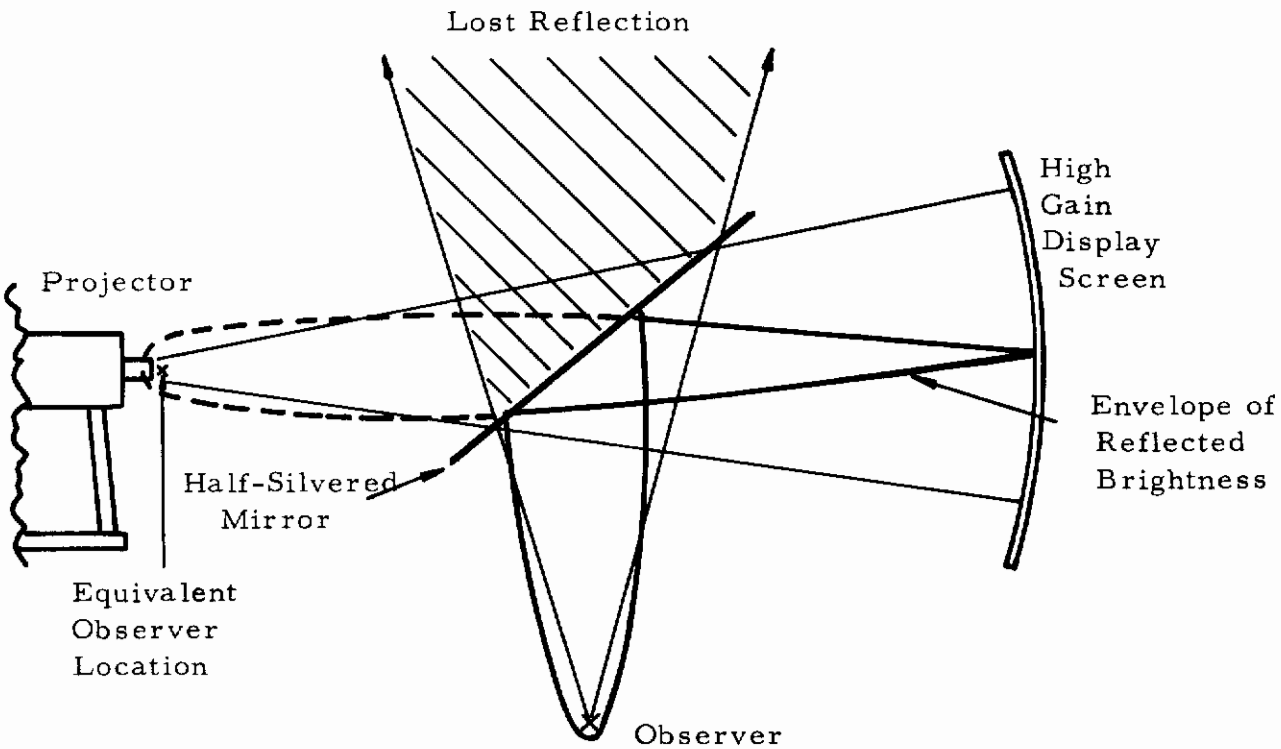


Figure 10. Projection Arrangement Using Mirror

conventional manner (for high gain surfaces), that is, in a narrow exit pupil. The reflected luminosity also strikes the mirror. Half is passed through the mirror to the projector and is not used. The other half is reflected from the mirror toward the observer. Thus the observer is unencumbered by equipment and still can be located in a position equivalent to the source of the projected image.

Note that such a system of viewing entails considerable loss of brightness; 50-percent of the luminous energy is directed away from the observer by the mirror since the light is reflected to the screen and is then reflected back from the screen. Only 25 percent of the original projected brightness (50 percent times 50 percent) reaches the observer. The advantage is that freedom of observer location allows the use of a narrow exit pupil from the high gain screen. Thus a screen with a possible gain of over 100, such as retro-reflectors, can be used in the system which itself has 25 percent efficiency, resulting in an apparent gain of (100 x 0.25 = 25) to the observer. Preliminary results indicate that further consideration of this arrangement is justified.

SECTION 4

DISPLAY DEVICE EVALUATION

INTRODUCTION

The contract required the development of a television projection device suitable for use with a 1029 scanning line television camera system. As originally conceived, many of the basic parts of such a projection device would be obtained from the F-151 Gunnery Trainer closed-circuit television (see previous sections). However, the projector of the F-151 would have to be modified to accommodate the higher deflection rates required to achieve the 1029-line scan, the video amplifier would have to be replaced with one of sufficient bandwidth to present a high resolution display, and the 7WP4 projection cathode-ray tube normally used in 525 scanning line systems of lower resolution would have to be evaluated as to its suitability for such a system before extensive development work could begin. The question was therefore what method of evaluation could be devised to determine tube capabilities prior to system development.

The conventional method of television system evaluation depends entirely upon observer evaluation. As will be explained later, this method has obvious limitations that rendered it unsatisfactory for the task at hand. Since all parts of a display system, e.g., deflection circuits and video amplifiers, can be analyzed separately and since defects or limitations in these components may give a false representation of display tube capability, it appeared desirable to devise an independent evaluation technique for the cathode-ray tube. Not only would such a technique predict the feasibility of applying the 7WP4 tube to a 1029-line system display projector, but, if really adequate, it could also be used for the evaluation of any or all display devices.

CONVENTIONAL EVALUATION METHOD

Evaluation of a television display has, to date, been achieved by what is termed "observer analysis". A test chart pattern (Figure 11) is produced on the display surface by a standard television camera, monoscope, or other high-quality image source. The observer is asked to discern the spacing of the lines at the chart centers and corners (note the areas of fine lines in Figure 11). What he reports is analyzed in terms of "resolution".

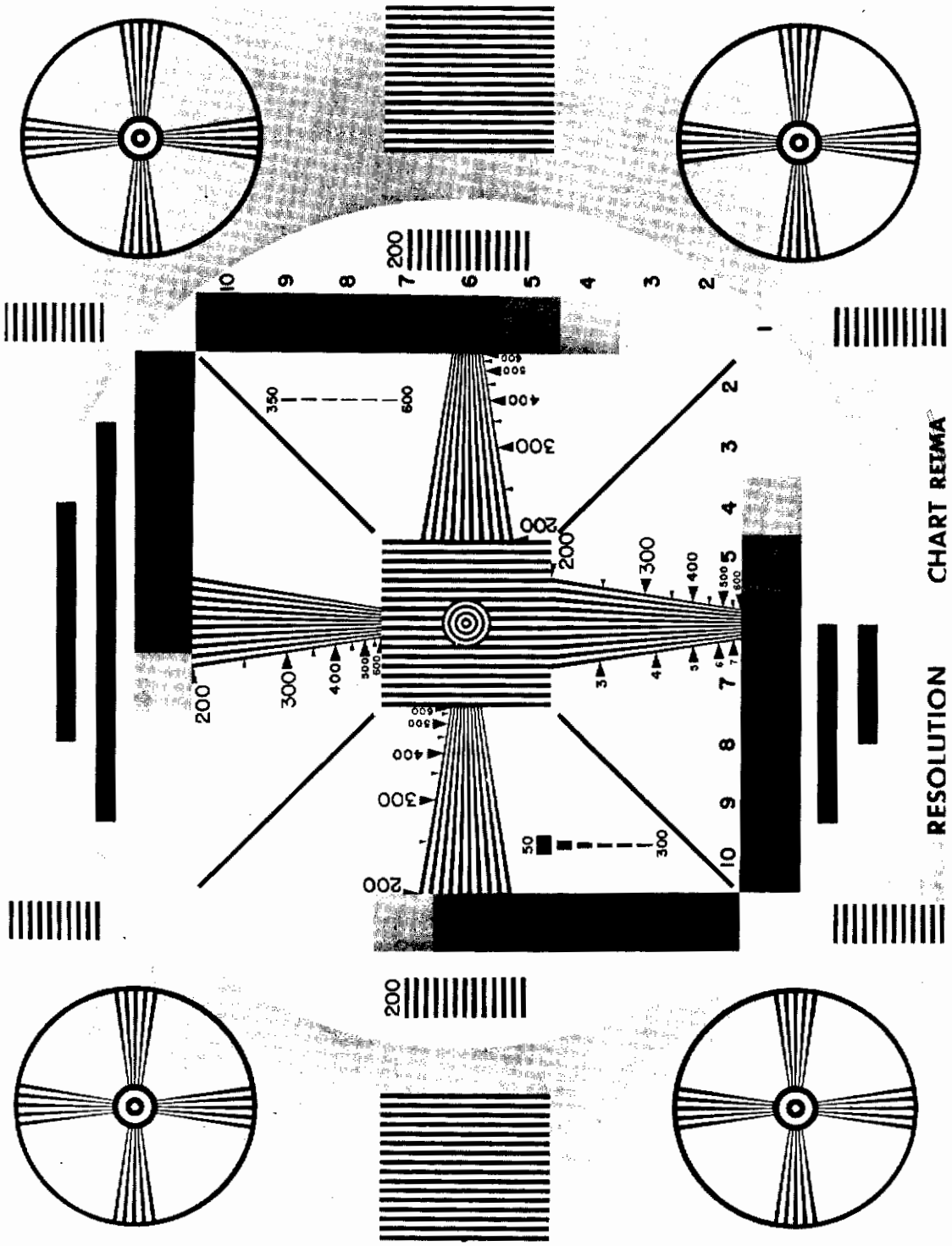


Figure 11. TV Resolution Chart

Television resolution is generally defined as the number of "lines", alternate stripes of black and white visible on the horizontal dimension of the picture equal to the vertical dimension; this industry definition does not consider the distance of the viewer from the screen although that is, in actuality, a considerable factor. Thus resolution actually means the number of bits of information that may be presented in a specified area. Note that on the chart the lines decrease in width and distance apart. The point at which the narrowest lines can still be distinguished is the point at which maximum resolution is measured. The number is indicative of the number of bits of information that may be presented on a scanning line.

Resolution is, in fact, developed by the different levels of light intensity produced by the system. It therefore becomes necessary for a proper definition of the image quality of a television display to give equal consideration to contrast ratio, grey scale, and brightness.

CONTRAST RATIO

The conventional method of observer evaluation does not produce a definitive measure of contrast ratio although contrast ratio is basic since resolution is discerned as different levels of intensity. In reality, resolution is more truly a pattern of brightness, and this pattern generates contrast, which is visible as light and dark areas.

In the ideal case, the black areas on the phosphor are totally black and therefore emit no energy (or a pre-set minimum), and the white areas emit energy at a maximum level. In the practical case this is true when one has low resolution images with large blocks of black and white. A high resolution image does not permit complete extinction of the phosphor in the dark areas because of such physical difficulties as spot size, phosphor decay, etc. Thus, at high resolution levels, the black areas are not truly black and tend to become grey, and the white areas tend to fall in level and to also become grey, though not as intense a hue.

In a scene presenting both coarse (low resolution, large blocks) and fine (high resolution, no large blocks) information, the coarse areas will exhibit good black-to-white contrast; the fine areas will not be as well defined and will appear as a dark-grey-to-light-grey

contrast. At the limit of resolution, of course, the difference is no longer discernible, and a uniform grey is seen instead of detail. This changing of contrast in the case of coarse and fine structures is known as "detail contrast" or "differential contrast". Obviously, it is highly important to the image quality, and, as obviously, it cannot be evaluated by the observer technique presently in use.

GREY SCALE

In a monochrome television system, one which is devoid of color in the display, relative intensity levels and hue are represented as shades of grey ranging from full white to completely black. Since detail is not limited to only white and black patterns, grey scale becomes an important aspect of resolution. As contrast ratio drops at higher resolution levels. The conventional method of observer evaluation of a system does not give a definitive value to the reproduction of grey tones. The only measure made is in terms of the 10 steps, or shades, of grey provided in large blocks on the test chart - - Figure 11. An adequate technique would permit measurement of grey scale reproduction at all levels of resolution and brightness, since the three are interrelated quantities which constitute display effectiveness.

BRIGHTNESS

The brightness level is the third element of image quality which cannot be evaluated definitely by observer analysis of the test pattern. It is known that the cathode-ray tube electron beam increases in size as beam current increases. This results in a correspondingly larger spot size and is most readily seen as an increase in the width of the scanning line. As a matter of fact, extremely high levels of current will cause a severe defocusing of the scanning spot termed "blooming". When these phenomena occur, display quality is degraded. Thus, resolution and grey scale rendition decrease at high brightness levels. Indeed, even below the level of blooming, a subtle increase in beam current will cause a noticeable degradation in resolution. Analysis at representative levels of beam current (brightness) is therefore extremely important.

APPROACHES TO AN IMPROVED SYSTEM

In view of the limitations inherent in the observer evaluation technique and the fact, previously mentioned, that camera tubes, video amplifiers, and other associated apparatus can introduce

errors as a result of their physical limitations, a search was undertaken to evolve a new, more effective evaluation technique for television displays.

SELECTION OF PARAMETERS FOR EVALUATION

The questions to be answered by an evaluation of a display device are what density of information can be written on a specified area of display surface, what contrast ratio results from such writing, and at what level of brightness can the other values be maintained.

A scanning line structure is written on the cathode-ray tube display surface by the television top-to-bottom and left-to-right scanning process. Thus, the entire display screen is energized in a coherent manner. Detail is presented on the display by controlling the level of excitation, and therefore, the intensity of presentation, in each small sector of the screen. The resulting pattern of bright and dark areas presents the desired image in tones of grey. The technical terminology for this phenomenon of intensity control is "z-axis modulation of the cathode-ray tube beam". The scanning line structure is, therefore, the vehicle for generating the brightness pattern on the television display surface.

Ordinarily, the scanning line pattern is oriented as a group of horizontal lines, and the number of lines determines the maximum number of bits of information that can be presented in the vertical plane. Obviously, a large number of lines is necessary (525 in U. S. broadcast television), and therefore the width of each line is kept at a minimum. Line width is limited by cathode-ray tube beam size, phosphor grain size, light diffusion due to phosphor thickness, and electron velocity. Thus, the line width represents the smallest information bit size that can be presented on the display device and indicates the maximum information density that can be presented at best operating conditions.

The basic scanning line is therefore a good parameter for evaluation of tube capability. Surely if lines are widely separated, a true black and white pattern at maximum contrast is obtained. As line spacing is decreased, the void between lines is no longer black, that is, there is a decreased contrast ratio. This method of pattern generation is equivalent to a test resolution pattern which spaces alternate black and white areas by intensity control signals (beam modulation of varying frequencies.

To review then, resolution is a pattern of alternate black and white lines or of alternate excited and unexcited (bright and dark) phosphor areas on the tube screen. Orientation of the pattern is not important since data taken in any plane can be mathematically related to other display dimensions. Thus, best resolution is the minimum spacing of bright and dark areas that will present an acceptable contrast ratio at the brightness levels desired.

IMAGE GENERATION

First attempts at improved evaluation centered about synthetic image generation. The generated image could be projected to a high gain viewing screen by the 7WP4 tube, and the large viewing screen could be photographed.

The most obvious approach was to use a conventional 525-line camera system with special test charts. The resultant display could be evaluated by the "shrinking raster" technique in which information density is increased by merely reducing the size of the display so that it covers only a portion of the display area: at one-half normal size, the resolution of a 500-line image would effectively represent 1000-line performance. Although the approach seemed feasible, it was unsuccessful because the 7WP4 tube cannot be operated at reduced display sizes. Increased concentration of power input to the screen in a small area would destroy the phosphor and perhaps cause failure of the cathode-ray tube envelope due to thermal stresses. Evaluation was restricted to evaluation at or near normal sweep sizes.

Since camera equipment was not available to generate a television image of 1000-line resolution at normal size, electronic image synthesis was considered. A method of inserting sinusoidal signals into the projected display via a conventional, high-level video amplifier was studied. The signal must be synchronous with the horizontal deflection, and blanking must be inserted to suppress the signal during the retrace interval. The resulting presentation would be a series of vertical bars having a sine-wave intensity distribution. The number of these bars would be proportional to oscillator frequency, which must be an exact multiple of the horizontal scanning frequency.

Equipment was assembled to attempt evaluation by this method, but the limitations and shortcomings were immediately obvious: to present a number of lines, in the order of 500 to 1000, the signal

generating oscillator must be exactly the 500th to 1000th multiple of the horizontal scanning rate. A very small discrepancy in frequency caused the resulting pattern to roll, jitter, or lose continuity completely (a "herringbone" pattern).

Since photographic analysis was contemplated, roll or jitter could not be tolerated at all, but it was found that the present state of the art does not allow stability between two signals, either from separate sources or from multiples of a common signal.

If such a signal were generated, it had to be processed through the projector video amplifier. However, development of an amplifier to provide over 80 volts of signal at a bandwidth of dc to 20 mc or greater was not practical for this purpose alone. Without such development this bandwidth would be limited, and the high resolution pattern would be severely degraded prior to cathode-ray presentation. The approach was therefore abandoned.

PHOTOGRAPHIC ANALYSIS

If a suitable display could be projected on a viewing screen, quantitative analysis of the scene would be necessary to eliminate the subjective variations that arise from observer analysis. Photographing the projected image is an obvious way to obtain a record of the display. Such an exposure could be developed as a transparency, and the transparency could be studied to determine display adequacy. Contrast ratio, for instance, would be obtained from microdensitometer analysis of the resolution pattern.

Obtaining such a resolution pattern proved to be quite difficult. The display brightness was low, so a long exposure time was necessary. Then the slightest instability in display projection caused a smear on the photograph. The two conditions of brightness and exposure time could not be reconciled to provide satisfactory transparencies, regardless of many attempts made using a variety of photographic methods.

The most notable of the attempts required conversion of the entire projection room into a box camera. A sliding shutter was placed in front of the projection lens; the room was darkened; and a sheet of film negative 8 by 10 inches in size was attached to the viewing screen. The shutter was manually opened to expose the film. Thus attenuating elements such as camera lens and screen

reflection dispersion were eliminated. However, adequate levels of projector light could not be obtained, and satisfactory photographs could not be produced. The photographic method was not pursued further.

DISPLAY EVALUATION BY SECONDARY TV ANALYSIS

In the process of experimentation with the techniques described above, a method of electronic analysis was developed which would eliminate the hazards encountered in earlier attempts.

IMAGE GENERATION

The only requirement in display is to generate alternate black and white patterns whose spacing is controllable. The raster of scanning lines, without brightness modulation, presents horizontal bars of brightness, and the void between lines presents a dark bar. Thus a vertical pattern of alternate white and black lines is inherent: no signal generation is required, video amplifier limitations are not introduced, and spacing may be controlled by adjustment of the vertical deflection size, a control that is conveniently available. Since the scanning line is, by system design, of a minimum width and actually represents the electron beam and phosphor spot sizes, all requirements for images are met without signal synthesis or modulation of the cathode-ray tube electron beam.

IMAGE DETECTION AND ANALYSIS

It became obvious that a television camera might detect a television image projected on a large screen better than film (though film is considered more sensitive or "faster") because the television camera tube can integrate, i.e. accumulate, light input over short periods. Experiments confirmed that a television camera can provide a representation of projected data adequate for the required analysis. Such signals acquired from television camera detection can readily be analyzed by conventional electronic devices, principally by using an oscilloscope which visually displays waveforms. Perament records are easily obtained by photographing these waveform displays.

The result of this thinking was the experimental setup shown in Figure 12. The image camera and projector image generator were used to provide an image to the projection unit for setup purposes only (focus size, etc). Thereafter, only a uniform white image was

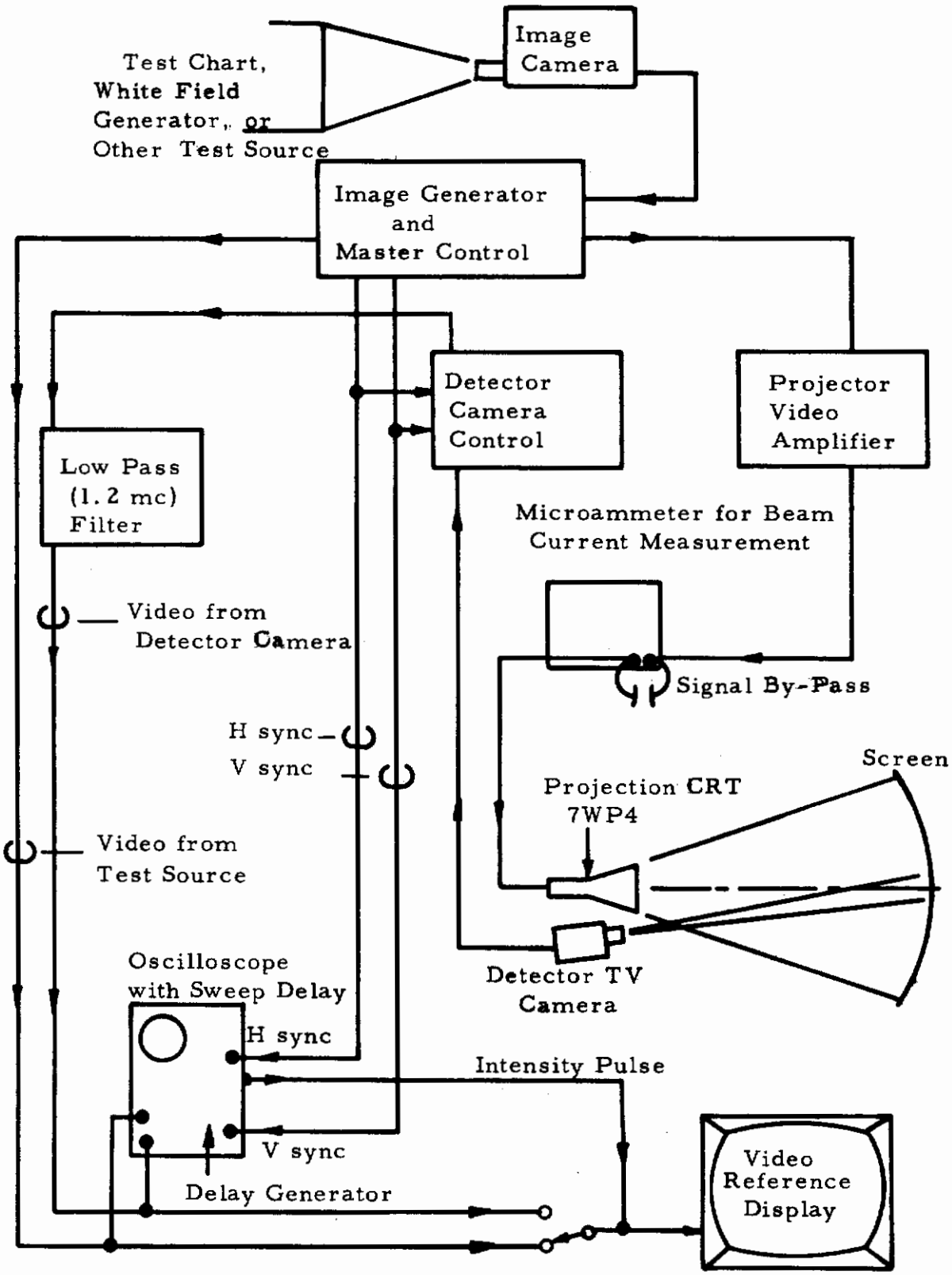
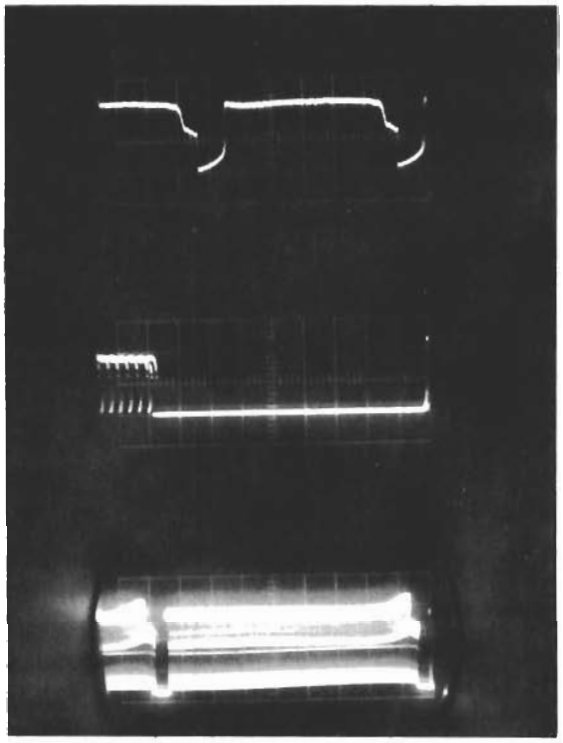


Figure 12. Test Set-Up and Equipment Layout for Evaluation of 7WP4 Projection Cathode-Ray Tube

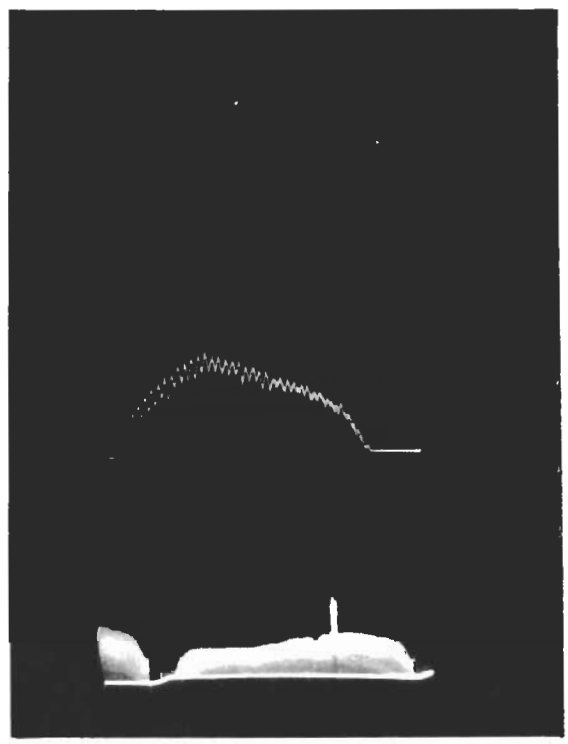
provided to the projector, and this signal was monitored using the oscilloscope. These signals are shown and explained in Figure 13 (a), (b), (c). The secondary television camera was used to detect the projected image, and the resulting signal was processed via the detector camera control unit. It was also convenient to use this control unit as the timing reference for the entire system. Note that both cameras and the projection (display) device employ one common sync generator to achieve a single timing reference. The detected signal displayed on the oscilloscope appeared as shown in Figure 13 (d), (e), (f). This was the waveform used for the analysis.



(a) An individual horizontal line of video showing detail of blanking and sync signal.

(b) Detail of vertical blanking and sync interval.

(c) Display of the vertical deflection interval of 16.667 μsec.



(d) Detail of horizontal line of detector camera scan as in (e) but magnified five times.

(e) One horizontal line of detector camera scan shown as surveying intensity profiles or projected lines. This line is located at the intensified point in (f) below.

(f) One field of detector camera as it accumulates information for 16.667 sec (262.5 horizontal lines). The spike indicates the particular horizontal line(s) being intensified and analyzed.

Figure 13. Typical Television Waveforms (Waveforms of video presented to projector unit and displayed on screen during evaluation. Note that flat white fields only are represented.)

EVOLUTION OF A PRACTICAL TECHNIQUE

Further work with the new technique evolved the following requirements for proper analysis:

1. The detector camera is best employed by "tipping" it on its side so that this camera tube is scanned in the vertical rather than the usual horizontal pattern (Figure 14).

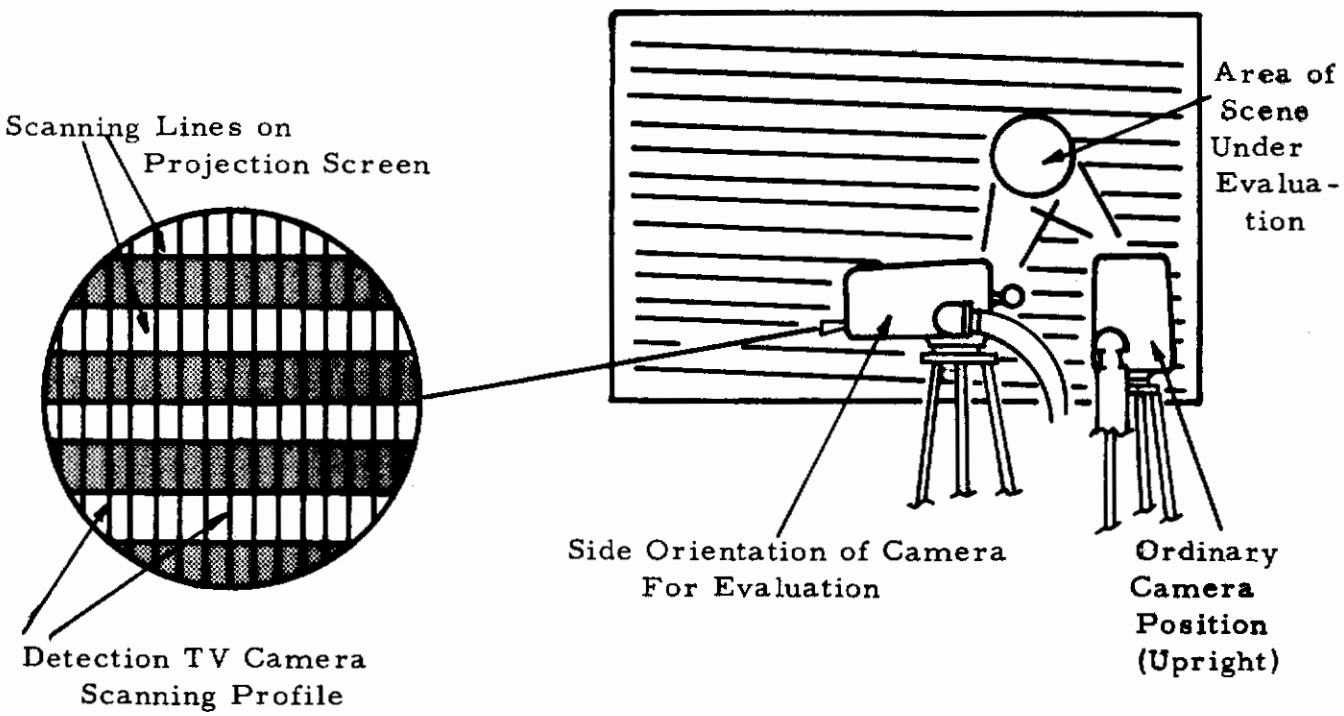
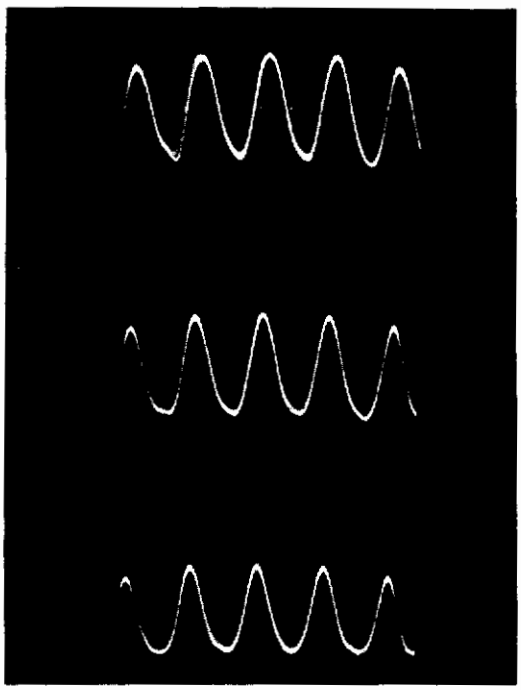


Figure 14. Camera Positioning

Thus the detector scans across the horizontal lines of the projected display. In this manner an intensity profile was obtained similar to a cross section of the projected data (Figure 15)



(a) 400-μa avg beam current
1064-μa peak current

(b) 300-μa avg current
789-μa peak current

(c) 200-μa avg current
532-μa peak current

Figure 15. Detector Waveforms (The presentation of scanning line structure under analysis. Oscilloscope display is magnified and data shown for varying beam currents obtained with 7WP4 projection kinescope.)

and a quite accurate measurement of contrast ratio and spot size represented by line width could be made.

2. It is only necessary to analyze a small number of the 262.5 scanning lines of a field, and good oscilloscope presentation can be obtained with no more than 20 to 40 lines. A minimum number of lines should be presented to the detector camera because the video bandwidth requirements of the detector channel are a consideration if analysis is not to be hampered by artificial limitations in the detection process.

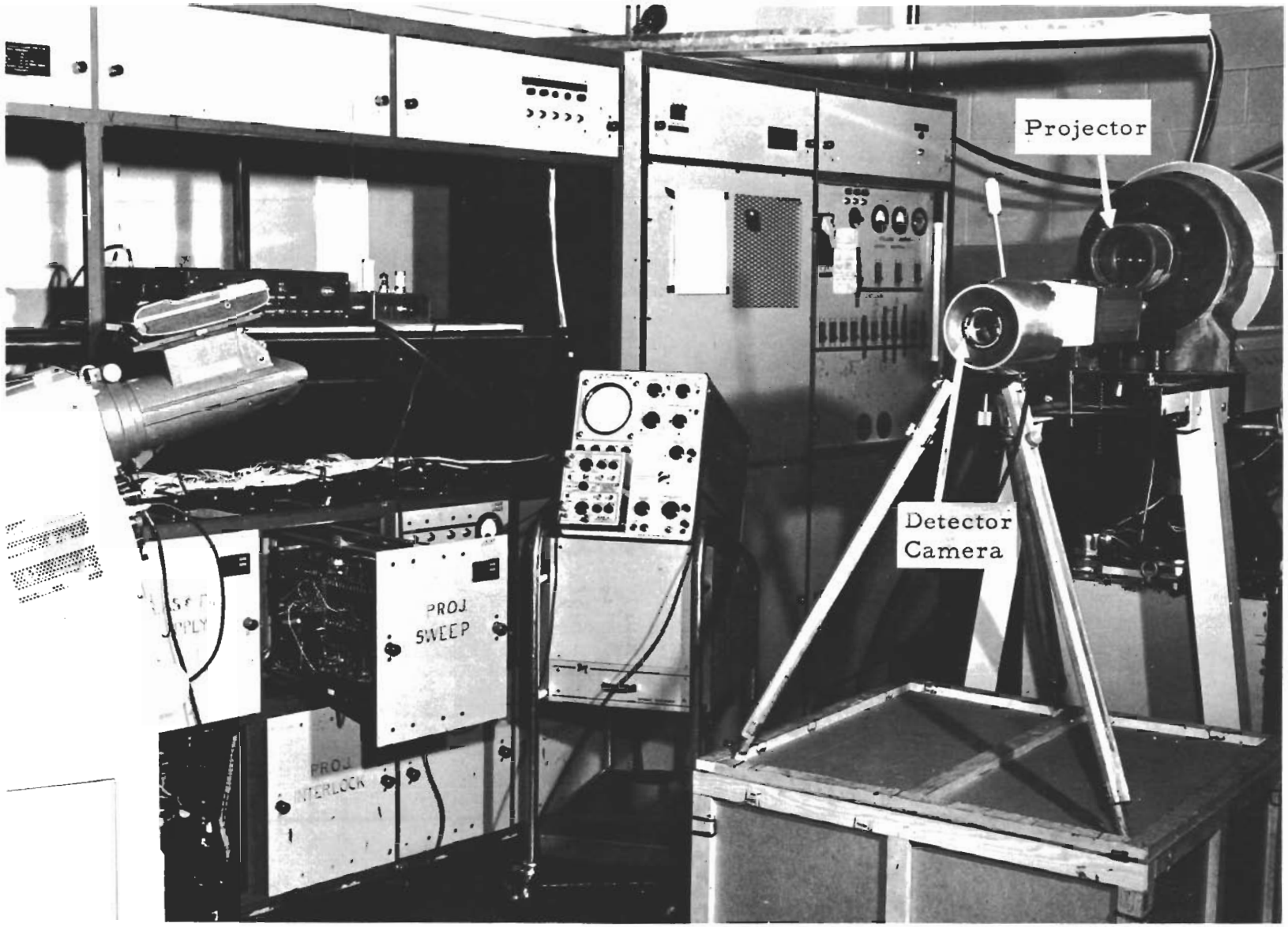


Figure 16. Detail of Projector and Detector Camera Physical Locations for Evaluation

The projected image was being detected in the scanning line of the detector camera (normally a horizontal line, but in this case, a vertical line -- see requirement #1 above). This line is capable of resolving up to 800 lines of resolution in the system employed, a General Precision Laboratory "Precision 800" closed-circuit television system. Thus, if only 20 lines were presented in this dimension, each line could be inspected at 40 points. The result should provide a more than adequate intensity and profile accuracy, and the detector camera bandwidth and resolution would be more than adequate for the purpose at hand.

3. To achieve a view of only a few scanning lines, as described above, the detector camera lens must have a very narrow viewing angle. Since a high gain screen which presented a very narrow exit pupil was employed, the camera had to be located close to the point of projection to obtain maximum benefit from light reflected from the screen. For this reason the camera was placed as shown in Figure 16. In this location a "Zoom" lens with a 4-inch focal length setting was found to be satisfactory. The resulting waveform displayed approximately 30 scanning lines (60 alternate black and white bits of information).

4. The use of a long focal length lens compounded the problem of brightness; such devices exhibit a high light attenuation rate, and therefore, a very low level signal was being detected. The waveform first observed on the oscilloscope was masked by random, high frequency noise, but the insertion again raised the question of bandwidth adequacy. If 60 bits of information are presented in a channel limited to 1.25-mc (150-line resolution) only 2.5 samples per bit are available although a minimum of 10 samples per bit is considered necessary. However, the 1.25-mc filter has a gradual rolloff characteristic, and partial response is obtained to 5 mc. Thus, the displayed waveform on the oscilloscope appeared to be a true representation. To verify this adequacy, a variable bandwidth amplifier with a response of 2, 4, 6, 8, and 10-mc was constructed and inserted into the system. It was found that objectionable noise did decrease as bandwidth was reduced but that the basic intensity profile of the projected data was accurately reproduced, even with the 1.25-mc filter. Therefore the passive filter remained in the system (Figure 12).

5. The testing procedure required a wide line separation of the projected data to insure a truly black line alternating with the white lines. This, in turn, dictated an increase in vertical size

of the display to obtain such separation to a point of "vertical overscan" of the cathode-ray tube screen. First attempts to achieve overscan were thwarted by unstable interlace and extreme nonlinearity. The conditions were corrected by repair of the vertical deflection oscillator circuit. Tests were attempted at twice the normal vertical size, but the interlace phenomenon and associated defects (pairing) prevented adequate separation of lines in adjacent fields. The only alternative was to remove ("blank") the line structure of every second field in every frame of data. This blanking was achieved by special gating circuitry, newly designed and made a temporary part of the projection sweep chassis (Figure 17).

6. The evaluation required an accurate measure of beam current to relate scanning line structure to display brightness because phosphor is directly related to electron beam current. First attempts were made utilizing the metering circuit of the projector control chassis. Subsequent investigation revealed that the system under test was not referred to ground but had a negative reference return within the oil-filled 80-kilovolt supply. A meter was therefore inserted in the cathode-ray tube cathode wiring to provide a direct measure of cathode-ray tube mean current.

7. Since the measurements for this evaluation required detailed analysis of the data contained in a certain scanning line of the detecting camera, it was necessary to display a specific segment of the television field viewed by the detecting camera on the oscilloscope. This was accomplished by "line-finding" techniques applied to an oscilloscope having a "delay trigger generator".

The "line-finding" technique is an exercise in timing various events in proper sequence. Assume, for example, that scan line number 100 in field 2 is to be examined. The reference point for this line is the vertical synchronizing signal for field 2, and it is known that line 100 appears 63.4 x 100 or 6340 μsec after the signal. Thus, if the vertical synchronous signal is connected to the delay trigger generator and is delayed 6340 μsec, the resulting delayed trigger will indicate the time for occurrence of the 100th scanning line. The delayed trigger is then routed to enable the oscilloscope to trigger off the next horizontal synchronizing pulse appearing at the normal trigger input terminal and thus to display the line desired. An enabling scheme rather than direct triggering with the delayed pulse was used to insure a stable display, independent of

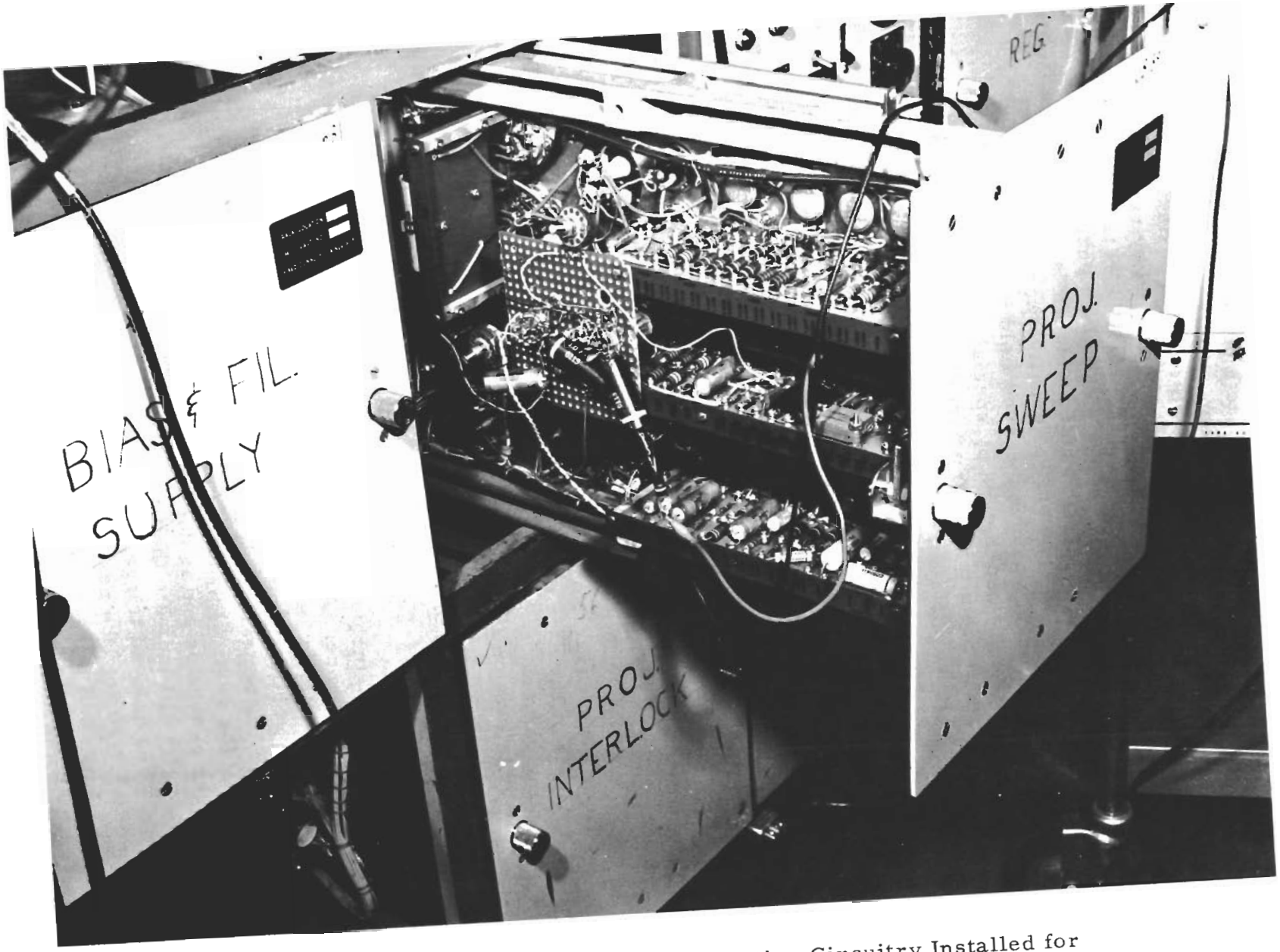


Figure 17. Detail of special Gating Circuitry Installed for Suppression of Every Second Video Field

any time discrepancies ("jitter") that might be introduced by the delay function. In this manner any single television scanning line could be examined by merely adjusting the delay time inserted into the vertical synchronous reference pulse. Details of oscilloscope connections for this procedure should be obtained from the manufacturer of the particular oscilloscope to be used.

Some oscilloscope manufacturers provide further convenience by providing an "intensifying pulse" output during the time of delayed horizontal line display. This pulse could be mixed into a monitor display, so the particular line being examined would appear brighter than the rest of the screen. A readily visible indication shows the line in which area of the display is being presented, without the tedious delay of time calibration or scan line counting.

SUMMARY

The evaluation of a 7WP4 was conducted using the arrangements described above. First results indicated a severe blooming above 500 μ ampere beam current, which implied that very low brightness levels must be maintained for good resolution. Complete data were obtained for the 7WP4 analysis and evaluation. The effort was concluded by making measurements of brightness versus beam current for both old and new display tubes and of sweep size versus sweep current. A detailed discussion of the evaluation will be found in Section 5.

SECTION 5

EVALUATION OF THE 7WP4 PROJECTION KINESCOPE

INTRODUCTION

The purpose underlying the effort to devise a method of cathode-ray tube evaluation was to determine the performance limitations of the 7WP4 projection cathode-ray tube in definite, quantitative terms. As previously stated, mere observation of a test chart pattern was not considered satisfactory. The requirement was to evaluate the 7WP4 in terms of contrast ratio, resolution, and brightness. Moreover, since these three parameters are interrelated, the data would have to show the proper relationships.

The technique and arrangement of equipment described in Section 4 were used to perform the evaluation. The results are presented in terms of

a. performance in the 525 scanning line system (measured)

b. performance in the 525 scanning line system (calculated)

c. measured and calculated results compared

d. performance in the 1029 scanning line system (calculated)

Then, based on the agreement of the measured and calculated data for the 525-line system, mathematical predictions are made of the performance to be obtained from the 7WP4 in a 1029-line system.

METHOD OF DATA ANALYSIS

RESOLUTION AND CONTRAST DETERMINATION

The limiting resolution in a cathode-ray tube is determined by cathode-ray tube "spot size". An undeflected beam striking a phosphor will generate a circular dot, or spot, of light at the point of beam impact. The size of this spot is determined by electron beam focus, beam velocity, and phosphor layer thickness and itself determines the minimum information bit size that can be presented on the display surface. As the beam is deflected in a horizontal plane, thus generating a bright line, the line width remains equal to spot size since there is no change in the vertical deflection of the spot

through a horizontal-line period. Therefore, scanning line width is an accurate measure of the cathode-ray tube spot characteristic.

The intensity output across the scanning spot is not uniform but is Gaussian in character, as shown in Figure 19. This means, of course, that the entire profile, as shown, will not be visible to the eye; a visual cutoff exists at a certain level in the waveform since the eye adapts to the bright average output of the phosphor. The intensity profile of the cathode-ray tube scanning line structure provided by the arrangement of the detector television camera and the oscilloscope display shown in Figure 12 was the basis for the contrast and resolution measurements made during this investigation.

The cathode-ray tube was adjusted for best focus, that is, for minimum intensity profile line width at the "Base Line" (see Figure 18). In these first tests, line spacing was set wide to insure the presence of unexcited black lines separating the white lines. Thus the detected line width "w" truly represents the spot size of the cathode-ray tube and therefore the minimum information bit size.

Photographs were taken of the oscilloscope waveforms representing these profiles (see Figure 13) and also while vertical deflection size was reduced to cause the profile spacing to decrease until an overlap of profiles resulted. The measured data were then plotted, and the results were compared with the contrast ratio and resolution predicted from the mathematical analysis described below.

Note that for the mathematical analysis the profile is sectioned into 0, 25, 50, 75, and 100-percent levels with a line width "w" of interest at each level, per Figure 18. The white line spacing is, obviously, the distance between the profile peaks and the corresponding portions of the profile.

Analysis is based on the data obtained from a plot of the intensity profiles (see Figure 19). In each instance the width of the line was first computed from photographs of the detected waveform. This computation was straightforward since overall deflection size in inches had been recorded, as had the number of scanning lines per field. The peak-to-peak spacing of the lines could be computed in inches. Then from this reference point, the waveform photographs could be scaled at other than the 50-percent level and the complete intensity profile drawn, as shown in Figure 19. The amplitude is

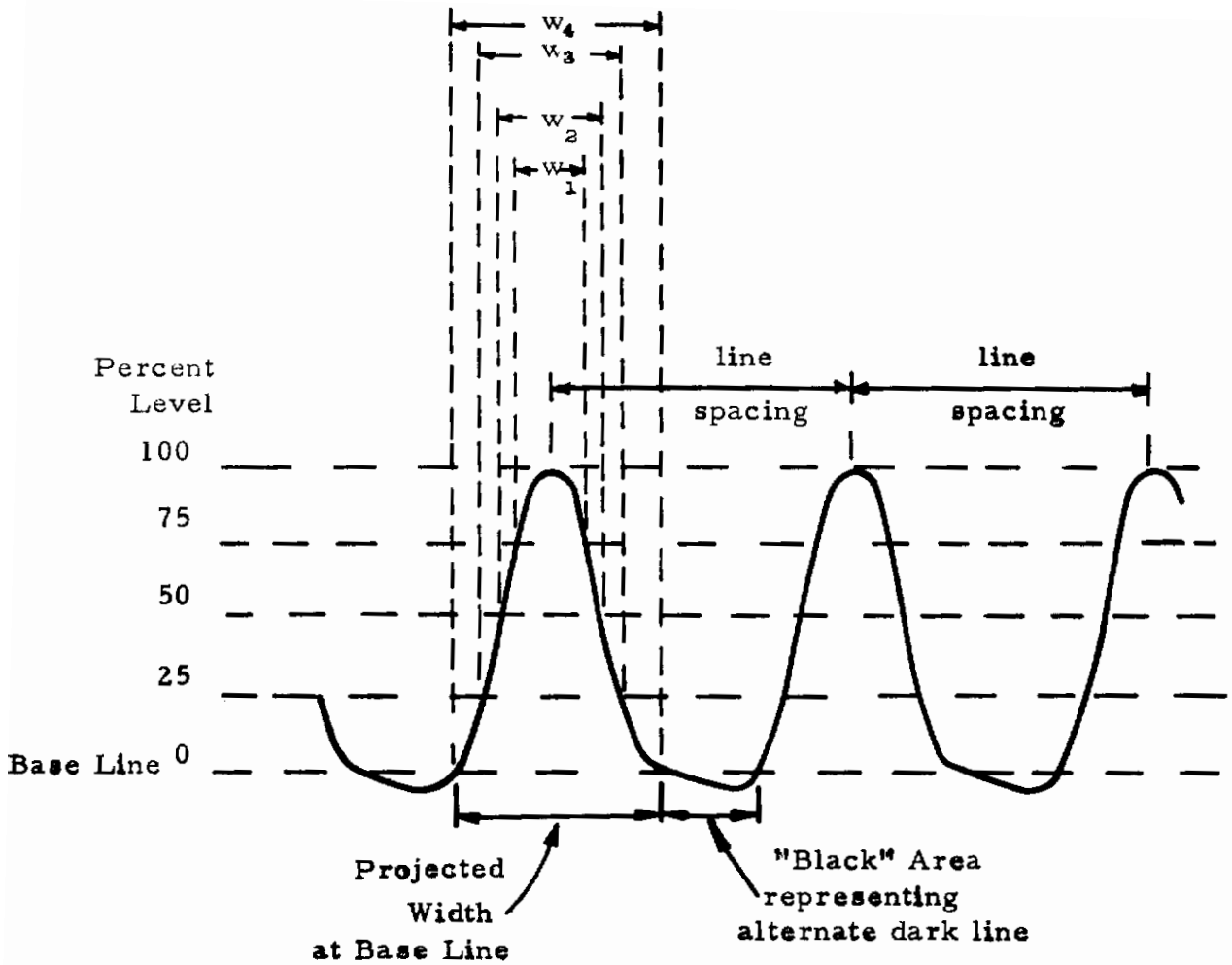


Figure 18. Waveform Evaluation and Analysis Format

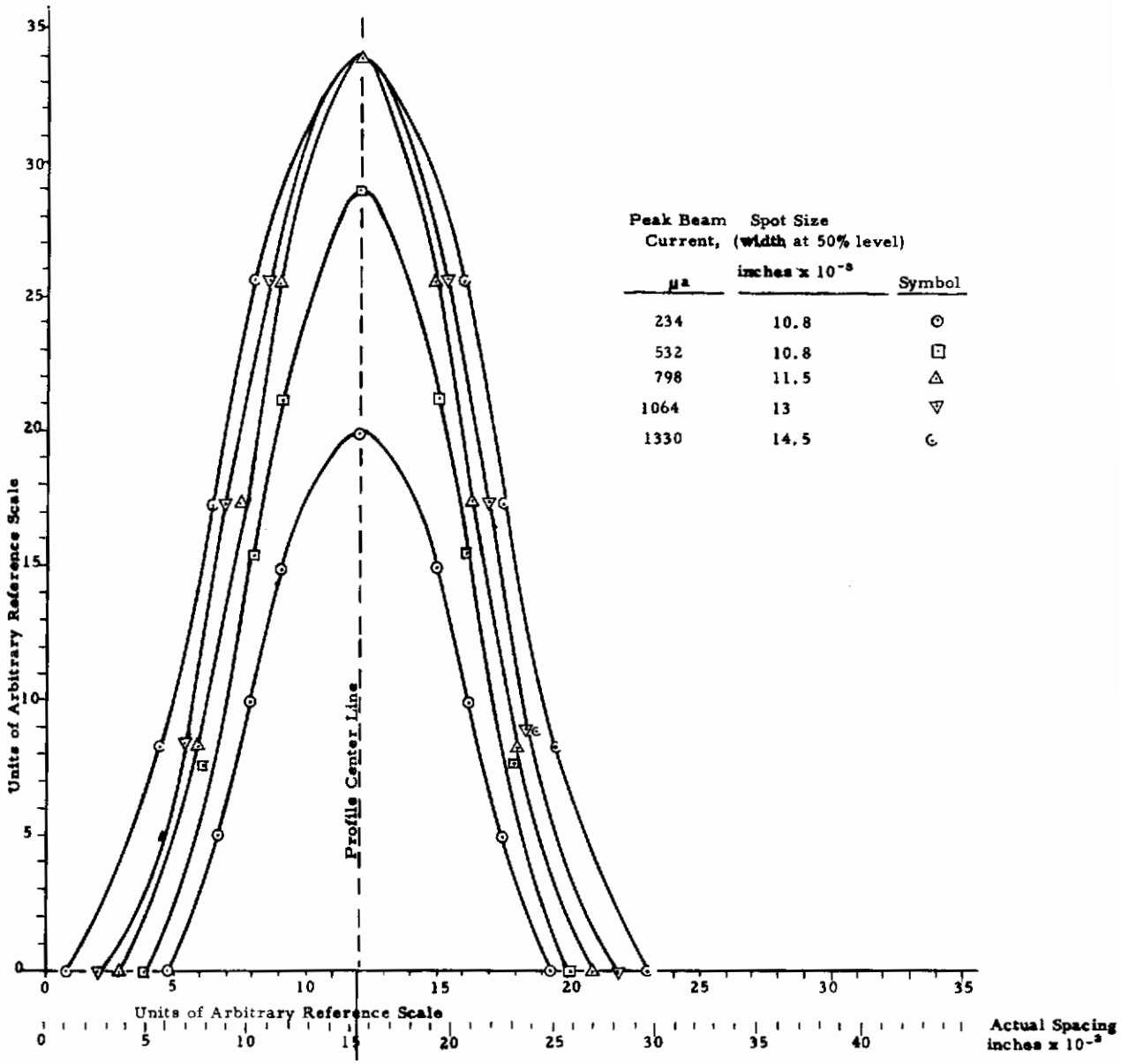


Figure 19. Scanning Line Intensity Profile

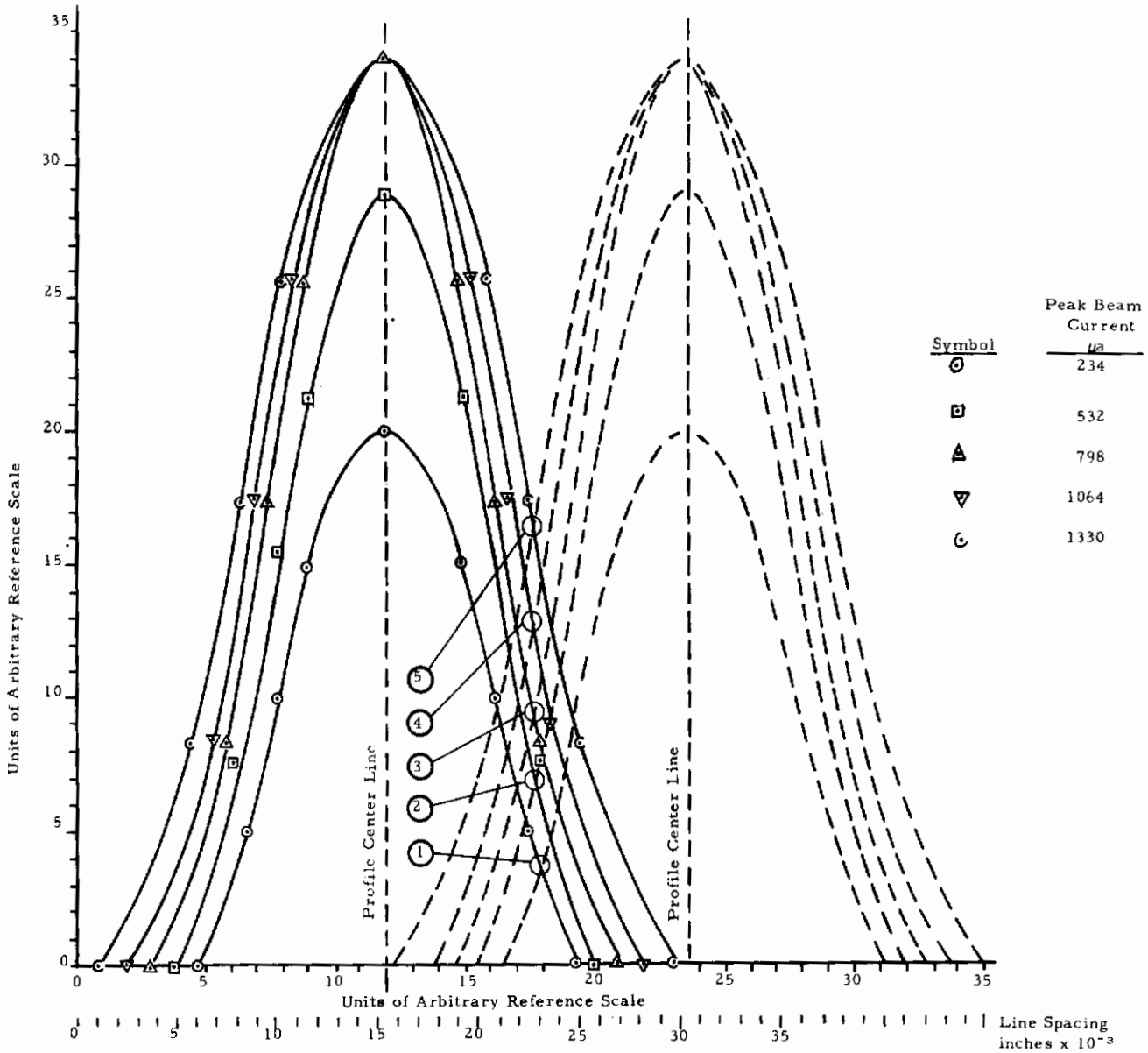


Figure 20. Scanning Line Intensity Profile Analysis

assigned an arbitrary scale for later reference. This rather complex series of steps is illustrated by the following sample problem.*

Measured Conditions

1. Vertical deflection size, total field = 6.94 inches

2. Number of active scanning lines = 241

3. Peak beam currents of 234, 532, 798, 1064, and 1330 microamperes

Analysis (see Figures 19 and 20)

1. Scanning line density =

$$\frac{\text{number of scanning line}}{\text{size of raster}} = \frac{241}{6.94} = 34.8 \text{ lines per inch}$$

2. Profile spacing (measured center to center) =

$$\frac{1}{34.8} = 0.286 \text{ inch}$$

for the case of 241 active scanning lines

3. If it is assumed that the desired presentation will present a 500-line resolution pattern on a 3.75-inch raster, then the resolution line density (the dark void between the profile peaks is considered a black line) is $\frac{500}{3.75} = 133$ lines per inch

the equivalent of a spacing of 0.0075 inch between resolution lines. The profile peaks (every other line in the bright-dark-bright-dark resolution sequence) then will be 15 mils (0.015 inch) apart.

Note that the interaction of adjacent lines may be predicted for various line spacings, representing resolution, by using an overlay of scanning line profile on the original drawing (see Figure 20 where the profile and overlay are illustrated with 15-mil spacing).

---

*A detailed analysis of all values is presented in Appendix IV.

Overlap does occur between adjacent bright lines, and it defiles the dark element of resolution present between the bright elements.

4. The data of interest for each individual beam current may be summarized as follows:

a. The intensity profile amplitude represents the intensity level. At a beam current of 234 microamperes, the line overlap for Test 1 occurs at 3.8 (as shown by 1 in Figure 20) on the amplitude scale. The luminous output is twice this value, or 7.6, because energy is contributed from each bright segment.

b. Since the peak intensity value is 20 units on the arbitrary scale at the current, the contrast ratio is calculated as follows:

$$\frac{20 - 7.6}{20} \times 100 = \frac{12.4}{20} \times 100 = 62 \text{ percent}$$

c. Thus a true white to black (100 percent) contrast ratio is not obtained, but a generally acceptable ratio of 62 percent is possible.

d. The obtainable contrast at each field of beam current may be tabulated as follows:

Current Condition No.	Peak Beam Current, Micro-amperes	Peak Intensity Value, Units	Crossover Intensity, Value x 2 =	% Contrast Ratio*
1	234	20	3.8 x 2 = 7.6	62
2	532	29	6.5 x 2 = 13.0	55
3	798	34	9.5 x 2 = 19.0	44
4	1064	34	13 x 2 = 26.0	23
5	1330	34	16 x 2 = 32	6

* Peak value minus actual value divided by peak value times 100. Note that for some conditions, the contrast may be represented by a negative number. In this case the overlap is so severe and occurs throughout so significant portion of the line that no contrast would be apparent since the data obscured by the black line would be completely lost.

BRIGHTNESS MEASUREMENTS

Equipment

Cathode-ray tube brightness output was measured with a spot brightness meter which has an optical system similar to that of a camera, except that a precisely calibrated photocell is employed in place of film. The meter optical system has a 1 - 1/2 degree viewing field and therefore measures light output over only a very small spot in the normal field of view. This photometer was arranged to view back through the projection lens to a small area of cathode-ray tube screen. The resulting field of view, as seen through the photometer eyepiece, is shown in Figure 21.

The overall vertical display size was recorded, and the number of active scanning lines was computed. A calculation of the photometric image size was therefore possible, based upon the number of scanning lines in view. In this manner it was determined that the photometer viewed a circular area 0.0622 inch in diameter. The visible display screen spot size was found to be 0.00389 inch (approximately 4 mils) at the low level of beam current used for the setup of the apparatus. However, this is not an ordinary operating condition for the 7WP4 projection tube. A very low beam current and brightness output were used for the setup of apparatus.

It is generally assumed that the intensity distribution across an excited phosphor spot is Gaussian in character, and that the phosphor excitation is visible to the half-value intensity point. The predicted spot sizes of 10.5 mils to 14 mils are obtained from the scanning line profiles on this basis, and are verified by manufacturers' data. The raster pattern of Figure 21 indicates that one should observe the white scanning lines and alternate dark lines. Such a pattern is usually observed upon closeup inspection of direct view displays.

The analysis indicates that one should not see such a light and dark pattern on the 7WP4 if the above method of spot size determination is followed. Scanning line spacing has been calculated at almost 8 mils for the 525-line raster in the usual 3.75 inch vertical raster height. Yet the spot size should be 11 mils or more, in which case the lines would merge and separation spacing would not be seen. Since observations prove that this is not the case, the assumption of half-value phosphor excitation being visible is subject to question.

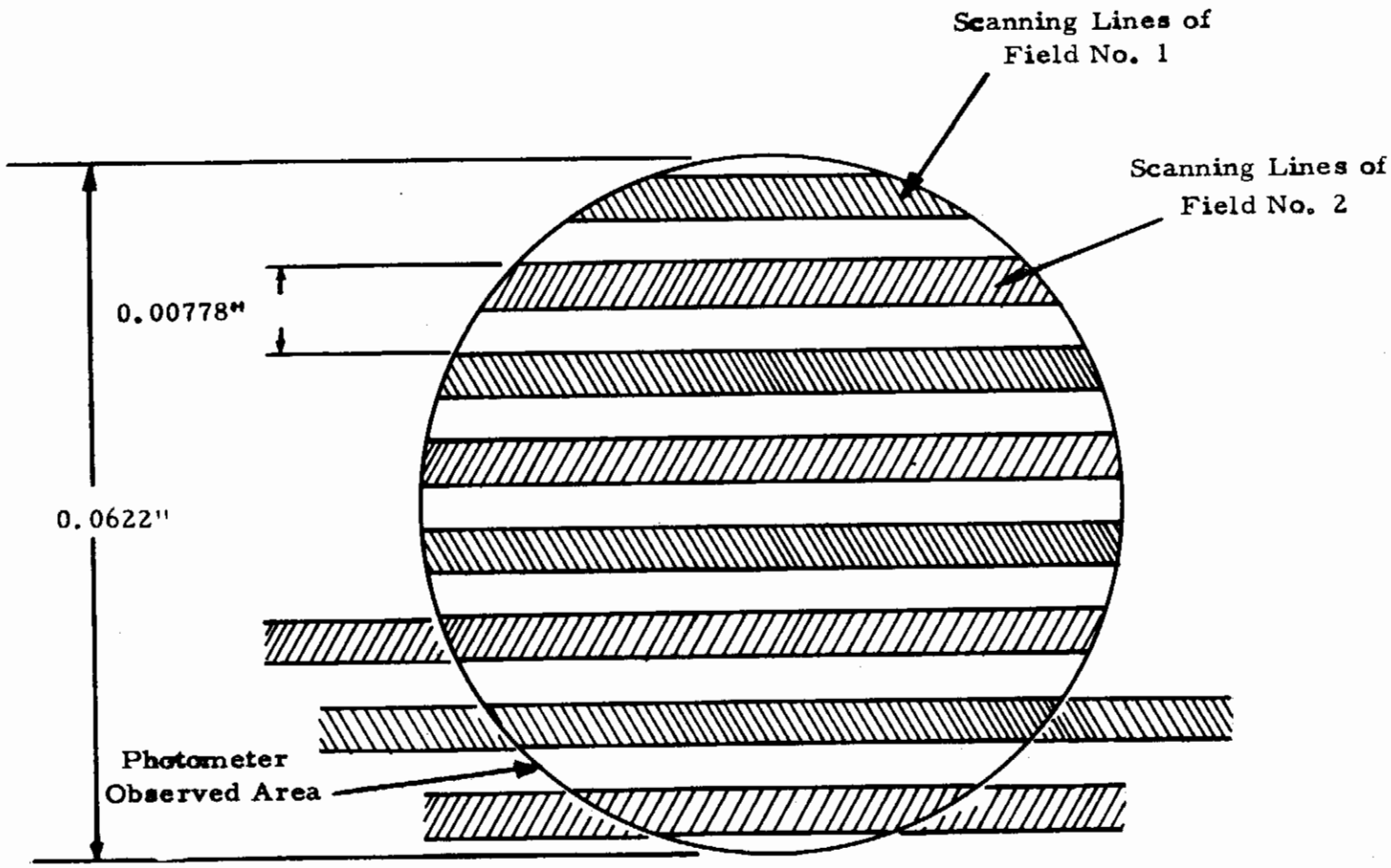


Figure 21. Observed Area of Kinescope Screen for Brightness Measurement

Spot size determinations are usually made by observation of an isolated, undeflected spot or an isolated scanning line on an otherwise unexcited phosphor. This is done by either instrument or visual observation of the surface in a shaded or darkened environment. Obviously this does not simulate actual operating conditions. The level of profile that is visible is directly related to the ambient illumination. In any cathode-ray tube displays, such an ambient level is obtained from many sources:

1. Diffusion within the phosphor.

2. Reflection within the glass faceplate.

3. Reflection of light emitted from the display.

4. Stray light from surroundings.

Therefore the "dark" void between scanning lines is far from truly dark, even though this phosphor is unexcited. Visual threshold will vary due to the ambient level, and the visible portion of the profile will be only that amount above the ambient level. Visible spot size may continue to appear less than 8 mils, preserving the appearance of scanning line structure even at beam current levels which generate a much larger spot at the traditional half-level point. It is concluded that the visible scanning spot is 4 mils at very low beam currents, and expands to 7 mils in normal operating ranges of less than 1000 μ ampere peak beam current. Above this value a scanning line structure probably will not be visible due to further increase in spot width.

Consideration of resolution is relatively independent of the spot size peculiarity outlined above. Of course resolution is ultimately limited by the spot diameter. The definition of resolution lines requires alternate dark and light area, which requires darkening of every other scanning line at the limiting value for vertical resolution. Thus a spacing of 16 mils between excited areas would be obtained in the example of Figure 21, and no spot overlap will occur even at half-level intensity profile points. The presence of ambient illumination does mean that absolute contrast ratio, the dynamic range in light intensity output from unexcited to excited phosphor areas, will be severely reduced. Relative contrast ratio is the quantity used in resolution testing and will remain unchanged by the ambient level. A technique which considers the absolute value is desired, but has not been developed. The effect of ambient level might be visually observed upon closest inspection of certain

patterns. If a number of parallel bars are displayed, such bars being alternately black and white and of equal width, and the displayed bar width approaches the spot size of the display phosphor, the visual effect would be an apparent narrowing of the white bar and widening of the dark bar. This is because the ambient level raises the threshold at which the excitation of phosphor is visible, thus only a smaller part of the spot is "active" and presenting data.

Measurements of cathode-ray tube brightness made looking through the projection lens rather than those made directly on the tube faceplate automatically factor in lens light attenuation, light scattering within the projector, etc. Thus the measurement is more properly a projector light output value for the 7WP4 at varying levels of beam current. This is a practical and realistic measurement since the tube is not used in direct display but always with lens and other elements between the tube and viewer. If the device were used with another type of projector (i.e., a Schmidt system rather than a refractive optics system), the absolute values might vary; however, the relative readings referred to a particular beam current in a specified format would be consistent, regardless of projector type.

Methods of Calculation

The fundamental quantity of any brightness evaluation is the amount of light output from a small area of the screen. Photometer measurements are obtained in terms of average light output in foot-lamberts and average beam current in microamperes. These measurements must be converted, for analysis, to more convenient units. A third parameter of equal importance in measuring brightness output is the speed of scanning.

Photometric measurements of light source intensity are generally expressed in candelas. Thus the measurement in foot-lamberts was converted to candelas for the area viewed with the photometer. Note that only half this area was excited (Figure 21); the cathode-ray tube screen output flux density (energy flow per unit area of source) is computed using the excited area only. In this manner the screen phosphor output may be calculated for each square inch of excited area. Then the only task remaining is to calculate the total excited phosphor area for the specified raster. This is not difficult since the scanning line length and width are measured by ordinary methods, that is, by visual

inspection.

Peak beam current rather than the more easily obtained average value was chosen for a reference in the analysis and in the brightness calculations because the average value is significant only in a specific context of video blanking time per field. Peak value is directly related to phosphor intensity, as shown on the intensity profiles, and any measurement can be related to different operating conditions and format from the peak current reference. The peak current was calculated by applying a correction factor to the measured average current value. This correction factor was obtained from the percent of video blanked periods in the projector input waveform.

In the case of the speed of scanning, it can be assumed that the output of phosphor spectral energy will be a direct function of the time that electron energy dwells on that spot. Therefore, speed of scanning or the time required to complete a scanning line will directly affect display brightness. For this reason, any data presented concerning scene brightness must specify the scanning line format, and, to be even more exact, the data must be presented in terms of the phosphor input energy product (microamperes times microseconds), as in this report.

The phosphor input energy product is calculated from raster size and beam current as follows:

1. Given scanning conditions of:

   field repetition rate 60 cycles per second
   scanning line rate 15,750 kilocycles (525 scanning line system)
   raster aspect ratio 4 x 3
   raster size, 5 inches by 3.75 inches

2. The length of the scanning line is established by the raster horizontal size at 5 inches.

3. The time to complete one scanning line is then $1/f = 1/15,750$ cps = 63.4 microseconds.

4. The active scanning line time is 63.4 microseconds minus the blanking time, that is,

$$t = 63.4 - t_{blank} = 63.4 - 13.6 - 49.8 \text{ microseconds}$$

$$\approx 50 \text{ microseconds}$$

Then for a 5-inch line scanned in 50 microseconds, the scanning line rate becomes 10 microseconds per inch of scanning line.

6. The rate multiplied by the beam current supplies the necessary input energy figure.

The same data could also be used to compute cathode-ray tube brightness output for any television format -- that is, raster size, number of scanning lines, aspect ratio, etc. However, all such calculations are valid only assuming the identical projection arrangement and application.

Data presented in the above manner can be used to interpolate from one format to another (i.e., from the 525-line system, 4 by 3 aspect ratio to the 1029-line system, 1 by 1 aspect ratio) as shown in the appendix. For instance, in a 1029 scanning line system with a 60-cycle-per-second field rate interlaced 2 to 1, the time per scanning line is reduced to $\left[1/1029/2 \right] 60 = 1/1029 \cdot 30 = 1/30,900 = 32.4$ microseconds per line. Assuming that 5 microseconds of this time is absorbed in a sweep return (flyback) and blanking, the active time for the scanning is only 27.4 microseconds. Assuming that a scanning line is 4 inches long for a 1 by 1 aspect ratio format, the energy output will result from only 27.4/4 microseconds per inch or 6.85 microseconds per inch. Therefore brightness output in this format would be 6.85/10 times the value measured for the 525-line system.

RESULTS OF ANALYSIS OF 7WP4 TUBE

As noted previously, the resolution of the 7WP4 display was evaluated by considering the adjacent scanning lines of one field as "white" bits of information. The voids between the lines were the alternate "black" bits. The contrast ratios* resulting from the varied spacing of these lines (Formats A and B) indicate tube performance for the respective information densities. (The information density was adjusted by means of the vertical size control. **)

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* In all cases an arbitrary 50-percent contrast ratio was selected as the minimum acceptable level. Observation indicates that detail may be visible with as little as 20-percent contrast ratio, considering full black-to-full-white contrast. However, a grey scale is an important factor of resolution and must be considered in setting this figure. At 100-percent contrast and low frequency, low resolution test blocks, 10 steps of grey may be seen with the better equipment. This, however, is the limiting value for system dynamic range, that is, few systems will produce more than 10 steps. Therefore, as the total dynamic range capability decreases, it is reasonable to assume that grey scale will be similarly degraded. In a linear system the grey scale would be limited to 5 steps at 50-percent dynamic range (contrast ratio). The graphs showing resolution reflect this assumption (5 steps at 50-percent range) in the selection of 50-percent contrast ratio as the minimum acceptable and also reflect the further assumption that as little as 5 steps of grey would be acceptable at the upper limit of resolution.

** Note that overscanning of projection tubes is not recommended since a high velocity electron beam striking the neck may liberate occluded gas and cause internal arcing. These tests of resolution were performed on older tubes that were considered expendable. However, no such failure occurred. Refinement of the procedure for use on newer tubes should provide protection from this phenomenon.

FORMAT A

Format A is the 525 scanning line system

interlaced 2 to 1
aspect ratio of 4 by 3
frame rate of 30 cycles per second
field rate of 60 cycles per second
raster size (7WP4) of 5 by 3.75 inches (width and height)

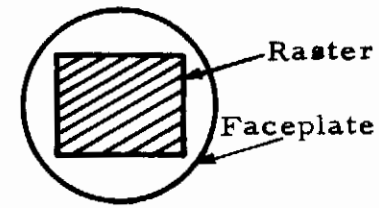
Format A is the normal operating mode of the 7WP4; the nominal resolution specification requires 450 television lines in a specified "quality rectangle". The results of the analysis of this format were then compared with observation and measured data to evaluate the analysis technique.

Analysis of the 7WP4 resolution and contrast ratio for Format A was performed as described earlier in this chapter. The results are plotted in Figures 22 and 23. Note that in the case of Figure 22, a dual scale is shown for the horizontal resolution curve to accommodate the industry definition of horizontal resolution ("the number of vertical lines discernible in a horizontal dimension equal to the picture height"). Thus, for the raster in question, the resolution, in television lines, would be the number of vertical lines discernible in 3.75 inches. The actual number of discernible elements would be 4/3 the television line specification.

Horizontal Resolution

The graphical representation of the horizontal resolution indicates that the acceptable limiting resolution (50-percent contrast ratio or greater for full black to white contrast)is 500 lines at low brightness but that this value decreases to only 385 lines as brightness increases to the highest brightness obtainable. Normal operation for systems employing the 7WP4 cathode-ray tube would therefore be centered in the range 375-500 lines; about 425 lines of acceptable resolution would be anticipated for Format A.

Data were obtained to permit direct plotting of horizontal resolution for comparison with the calculated values (see appendix and Figure 22). The observed values are lower than the analysis predicts, to a 20-percent deviation in one case. This degree of experimental error is believed to be the result of the following:



Scanning Format:
4 x 3 Aspect Ratio, Interlaced 2:1
Horizontal Raster Size is 5 inches

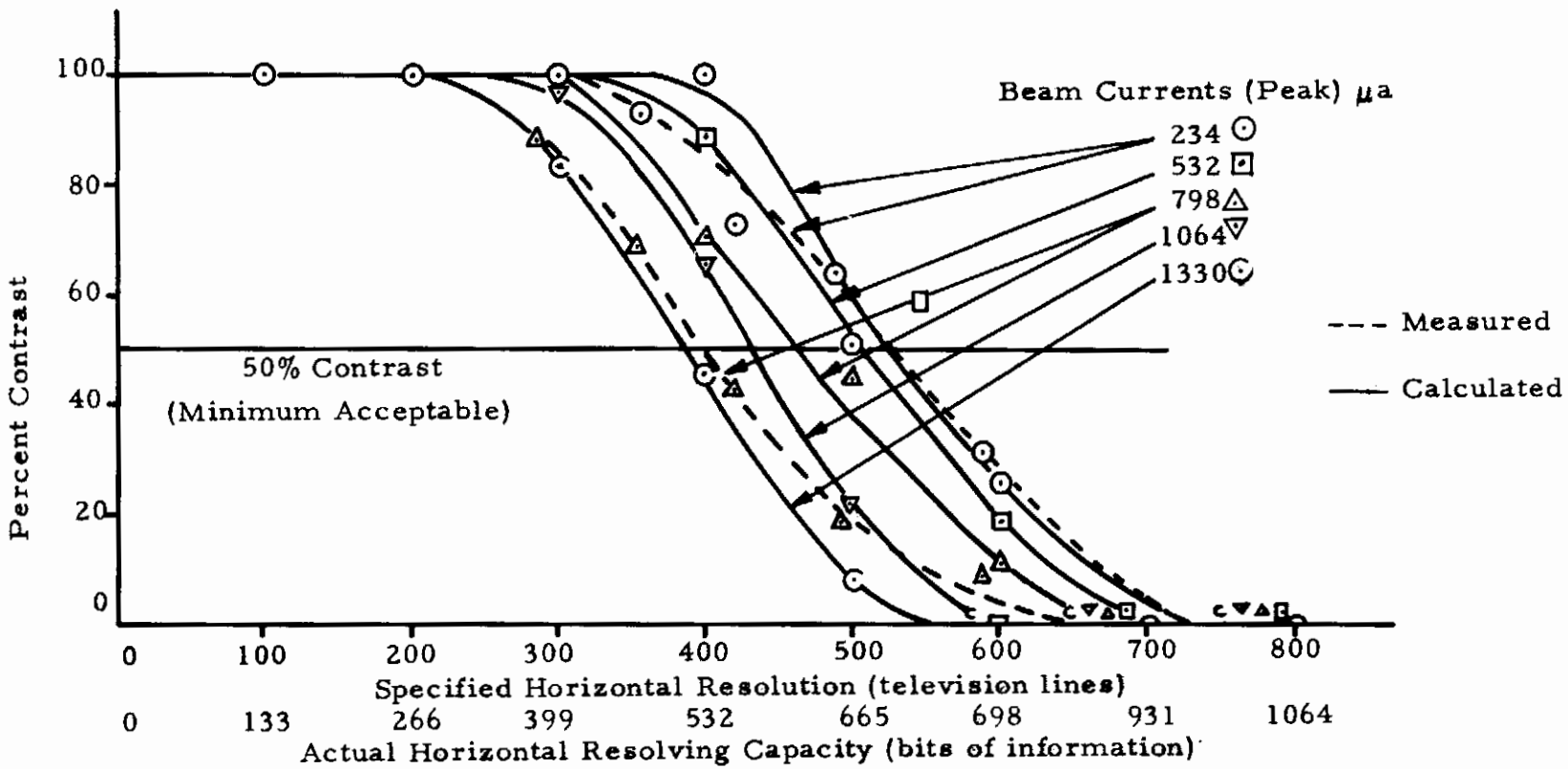


Figure 22. Horizontal Percent Contrast vs Resolution for 525 Line System

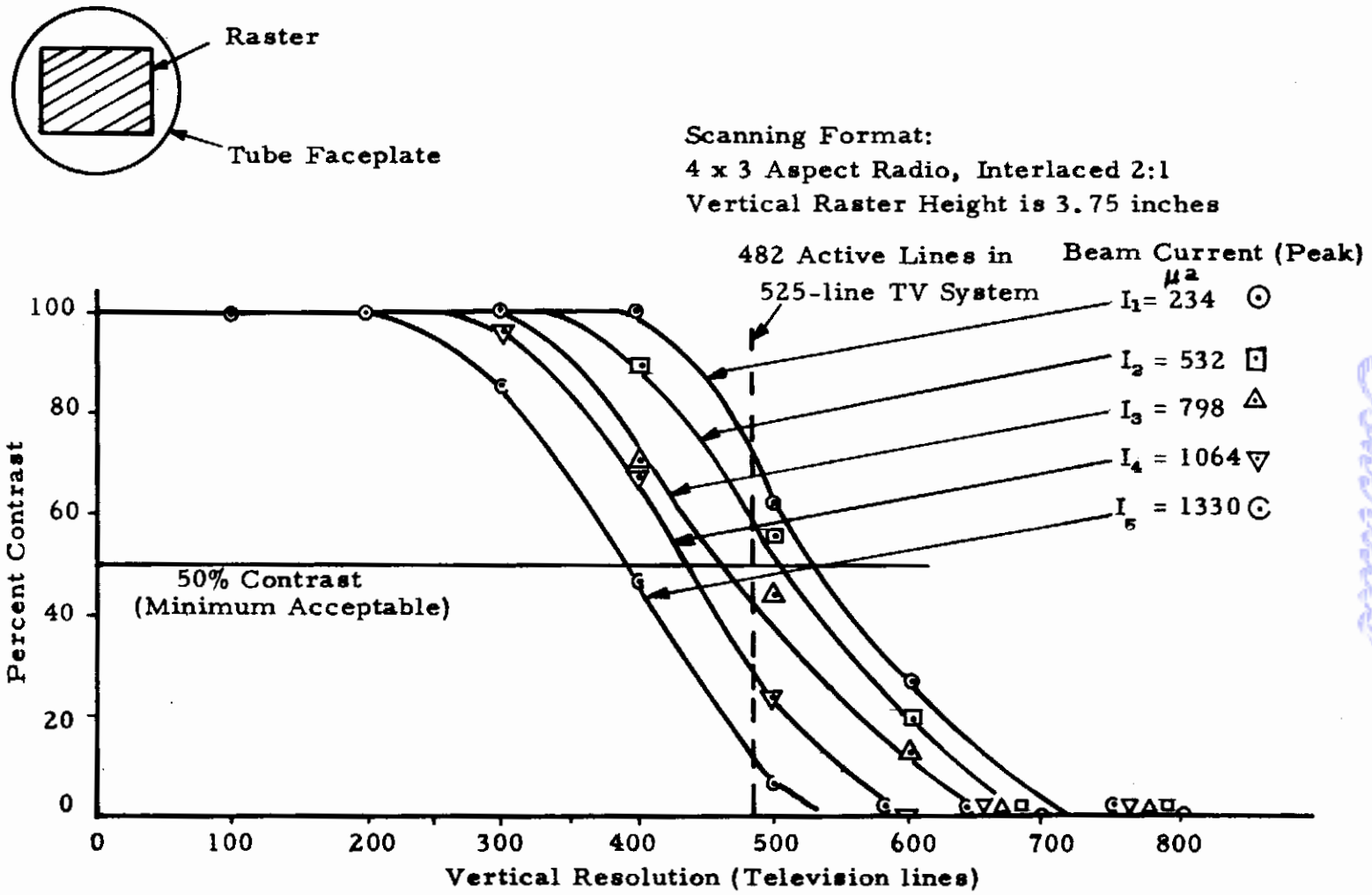


Figure 23. Vertical Percent Contrast vs Resolution for 525-line System

1. Only a few data points were available; curves of data are interpolated between widely spaced points.

2. Data on line width and contrast ratio were obtained from small photographs; there is the probability of deviation in graphical analysis.

3. Some additional defocusing or "blooming" may be occurring at higher beam current levels; this would contribute to more pronounced levels of degradation at higher beam current levels. The graphical analysis does not show the effects of such fringing.

The calculated values obtained by the analytical method are admittedly optimistic and indicate the maximum performance that can be expected under best (ideal) conditions. However, the results shown compare favorably with direct observation of the projected test chart.

Vertical Resolution

Vertical resolution is actually somewhat inflexible since it is established by the number of scanning lines. A graphical representation can only indicate the quality obtained at the given number. It is known that 482 active scanning lines will be present in the 525-line system (see appendix), but the contrast ratio at that point is to be determined. Note that an acceptable contrast ratio (50 percent or more) is obtained up to only moderate beam current levels. Therefore the tube presents acceptable data through only part of the operating range.

Exactly 482 lines of vertical resolution will not be visible to the observer because the supposedly horizontal scanning line contains a slight pitch, usually the right side being slightly lower than the left. This is inherent in the scanning sequence which writes horizontal lines while gradually proceeding from the top to the bottom of the raster. A multiplying factor of 0.7 is therefore generally applied to vertical resolution (the Kell factor after R. D. Kell and others, see references 2 and 3, p. 83). Thus the viewer should expect only 335 discernible lines of acceptable vertical resolution from operation with Format A rather than 482, the number of scanning lines.

Brightness

Brightness output of the tube is presented in Figure 24. The calculated values were obtained using the analysis technique described in Section 4. It was not necessary to factor in speed of scanning for this case since the measurements and the calculated values were for the same format. The new tube produced considerable brightness, as much as 320 foot-lamberts at 1-milliampere beam current (average). Unfortunately this value decreased to only 150 foot-lamberts, less than half the original value, after less than 200 hours of operation because of the browning of the face plate. This naturally occurs when silicon glass is subjected to 80 kilovolts, the level of voltage used for 7WP4 beam acceleration.

Comparison of Old and New Tubes

The calculated and measured values shown for the older tube agree closely, providing verification for the technique and for the assumptions made in the calculation and analysis of the data. A complete summary of 7WP4 operation is presented in Table 1.

Table 1

7WP4 CHARACTERISTIC VALUES FOR FORMAT A*

Reference Values		Brightness**, Foot-Lamberts		Resolution	
Avg Beam Current, μa	Peak Beam Current μa	New Tube	Old Tube	Acceptable Horizontal TV Lines	Contrast Ratio Vertical Res, %
160	234	70	31	525	72
375	532	142	63	505	56
560	798	198	88	465	42***
765	1064	257	118	430	27***
955	1330	312	146	385	12***

* See specifications for Format A
** See Figure 24
*** Not acceptable

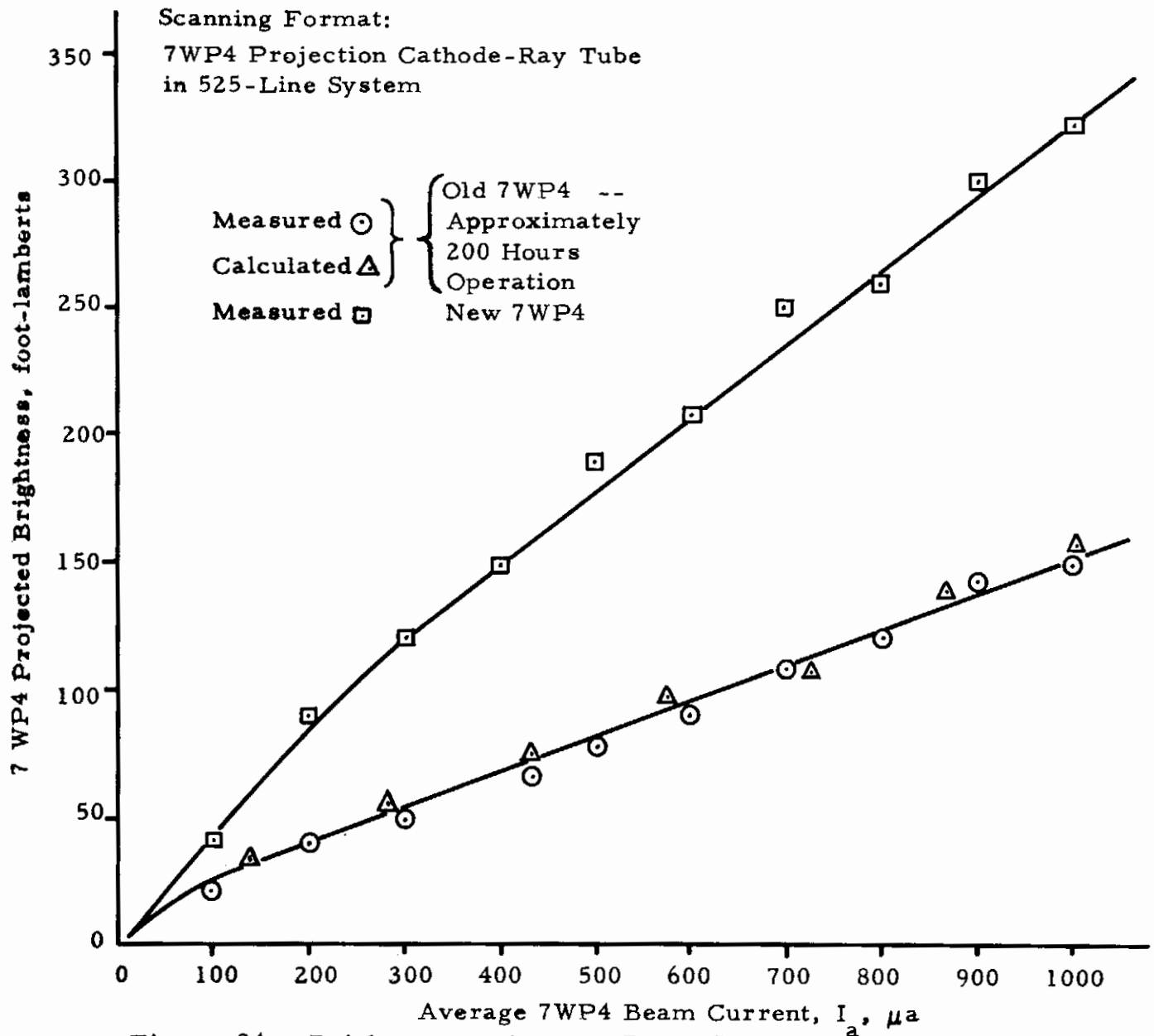


Figure 24. Brightness vs Average Beam Current Comparing New Tube Output and Output for Tube Used Approximately 200 Hours

FORMAT B

Format B is the 1029 scanning line system

interlaced 2 to 1
aspect ratio of 1 by 1
frame rate of 30 cycles per second
field rate of 60 cycles per second
raster size (7WP4) of 4 inches square

Format B, described above, is envisioned as a future possible application for television refractive projection devices, particularly the 7WP4 and associated existing enclosures.

The analytical procedure outlined in Section 4 and described previously was used. A 1000-line resolution display, both horizontal and vertical, was desired.

The results of the analysis of resolution and contrast ratio is presented in Figures 25 and 26. Note that since the aspect ratio is 1 by 1, the number of horizontal television lines is a true indication of the horizontal elements in a distance equal to the picture height which is, in fact, the width of the picture. Therefore the multiplier employed in Format A calculations does not apply, and the dual scale is not required in Figure 25.

The graphical representation of horizontal resolution appears somewhat pessimistic. It does not seem possible to obtain 1000 lines of display, even with lower levels of contrast ratio. If the 50-percent contrast ratio is considered the minimum acceptable, only low levels of resolution are possible. The range is then from 560 television lines at low beam current levels to 400 television lines at high beam current levels, with an average of 475 lines in the average operating range.

The conditions are somewhat similar for vertical resolution. The desired level of contrast ratio cannot be achieved with the 942 active scanning lines in the raster. It must be concluded that the tube is not suited to this format; a scanning line structure will not be visible in the raster. Average available resolution will be in the order of 475 lines.

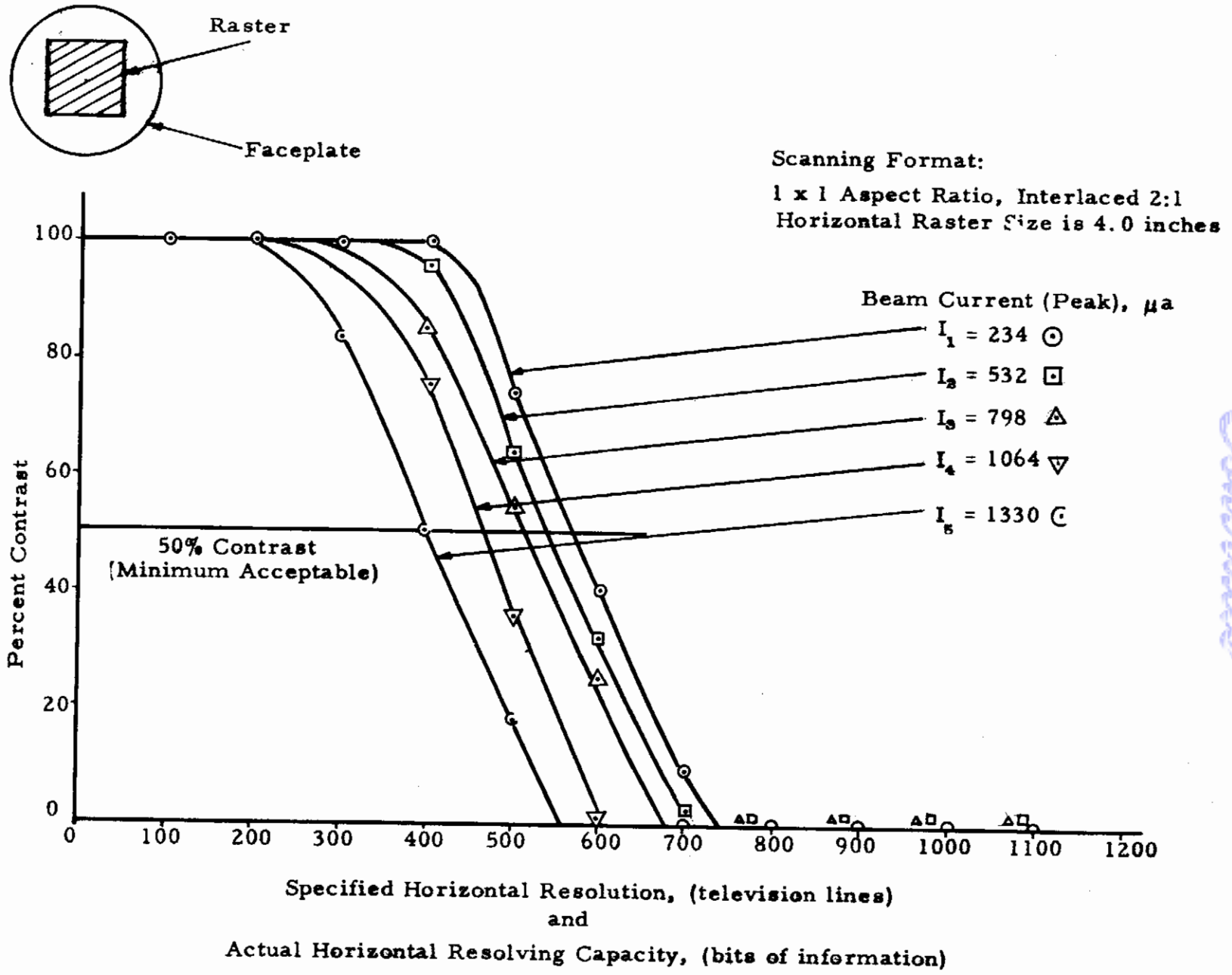


Figure 25. Horizontal Percent Contrast vs Resolution for 1029 System

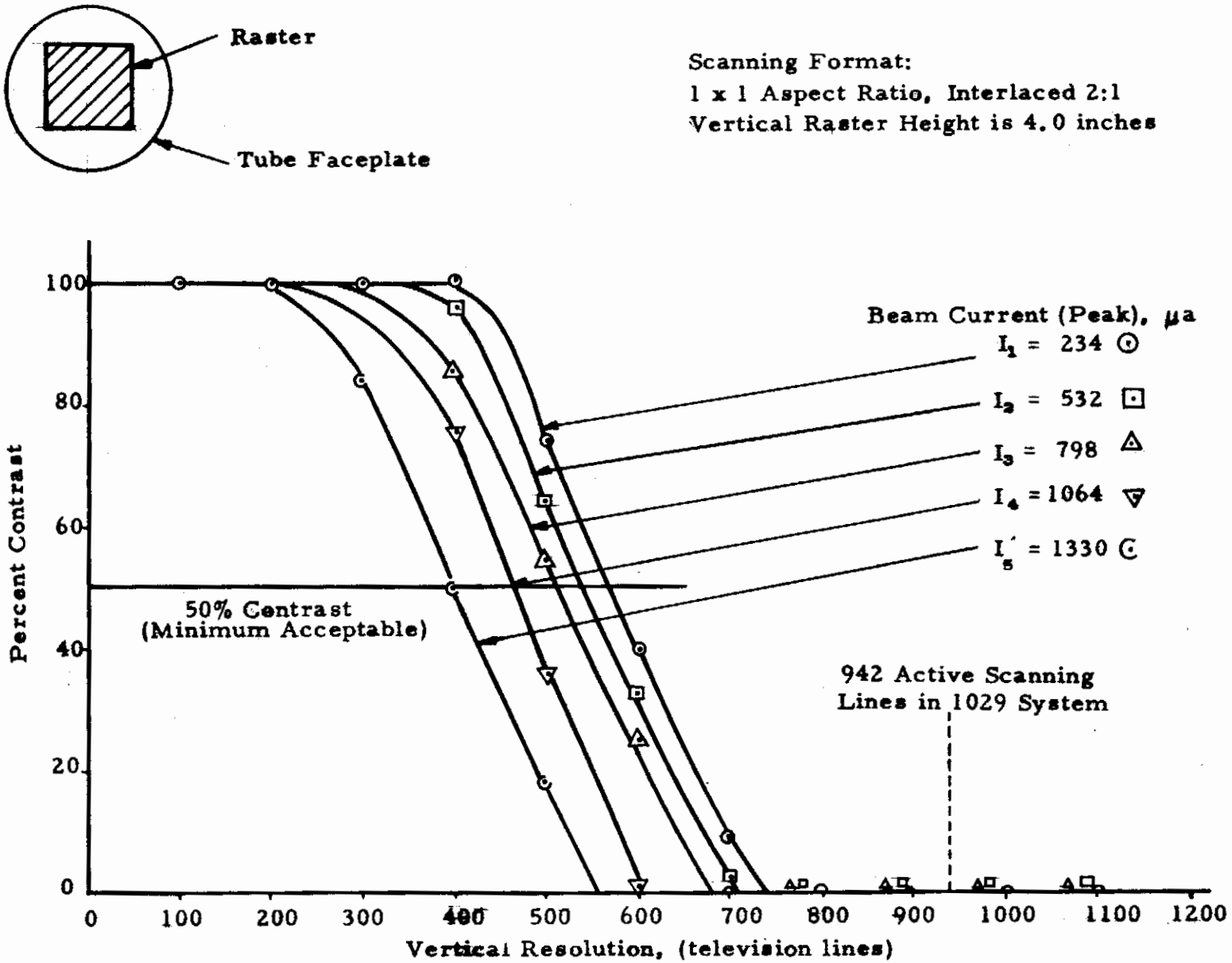


Figure 26. Vertical Percent Contrast vs Resolution for 1029 Line System

A prediction of the brightness of the 7WP4 when it is utilized in Format B was also made using the analysis technique described above. The results are shown in Figure 27. Note that the data points indicate an increased brightness of display, approximately 1.25 times greater than that indicated for Format A. This is surprising, but can be expected because the information density is greater -- 942 scanning lines are presented in a 4 by 4-inch raster (16 square inches) for the 1029-line system versus 482 lines in a 5 by 3.75 raster (18.75 square inches) for the 525-line system. Thus for an equivalent peak beam current and phosphor output light flux, a much greater concentration of energy is presented in a smaller area for the case of the 1029-line system, even though the phosphor is being scanned almost 1.5 times faster. (This assumes that faster scanning of the display surface will permit full excitation of the phosphor. Tests must be performed to validate this assumption; however, it is realistic to assume that output brightness will increase because of the larger information density.)

A complete summary of the calculated 7WP4 operation in a 1029 scanning line system is presented in Table 2.

Table 2

7WP4 CHARACTERISTIC VALUES FOR FORMAT B*

Reference Values		Brightness**, Foot-lamberts		Resolution	
Avg Beam Current, μa	Peak Beam Current μa	New Tube	Old Tube	Acceptable Horizontal TV Lines	Contrast Ratio Vertical Res, %
175	234	84	43	560	0
410	532	170	86	533	0
610	798	237	115	510	0
820	1064	312	158	466	0
1030	1330	400	190	400	0

Not Acceptable

* See specifications for Format B
** See Figure 27

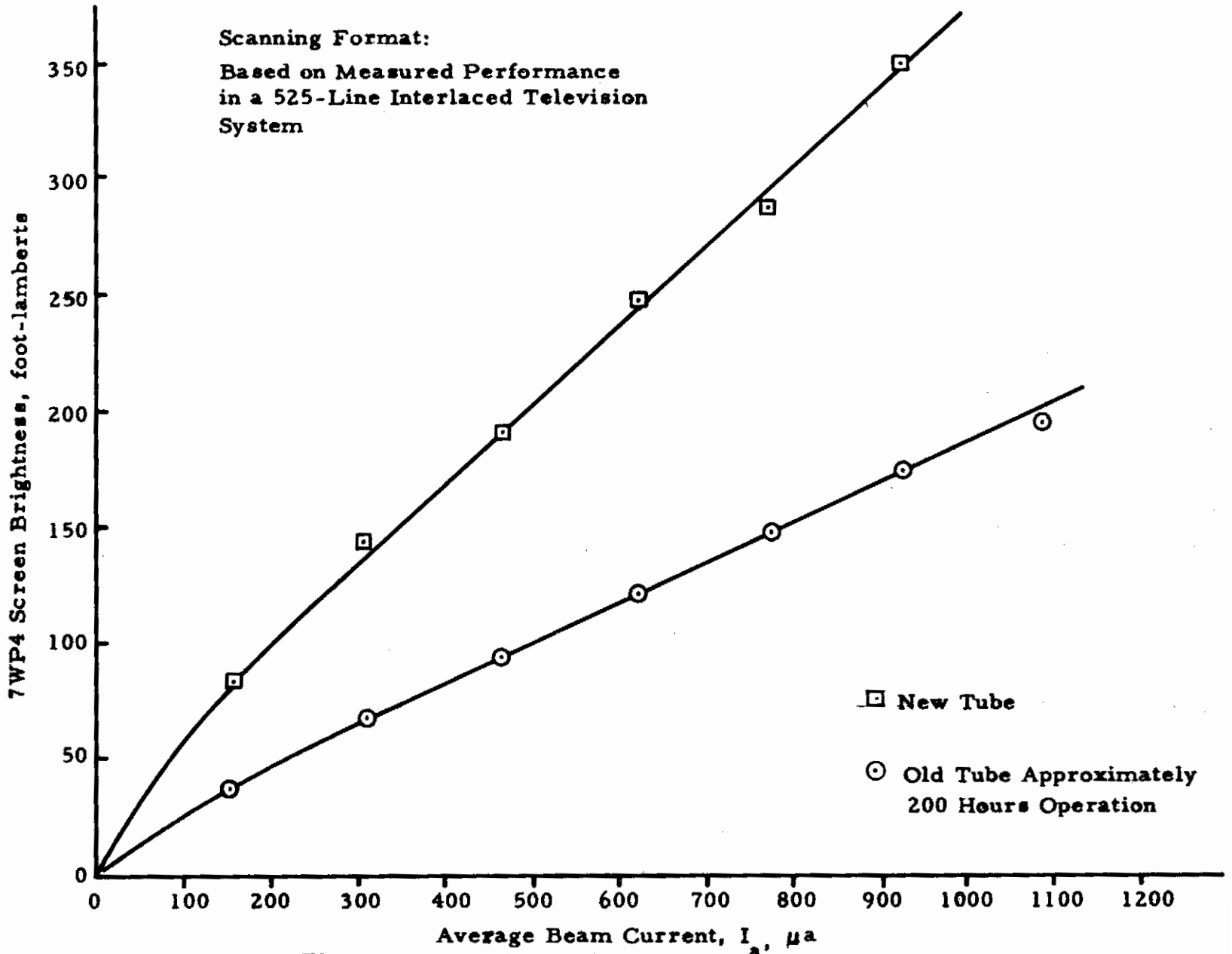


Figure 27. Calculated Brightness vs Average Beam Current for 7WP4 Projection Cathode-Ray Tube Used in 1029-Line Interlaced Television System

ADDITIONAL RESULTS OF 7WP4 ANALYSIS

The 7WP4 projection kinescope was designed for a fairly high intensity display in a 525-line, interlaced television format. Data for operation under these conditions are presented throughout the previous discussion. The following points are worthy of note:

The most obvious tube characteristic determined by the analysis was the behavior of spot size. As predicted by the literature, the scanning line width (that is, spot size) does increase as beam current increases (see Figure 28). This implies that the limit of resolution will decrease as brightness increases since resolution is limited by beam spot size and brightness is a direct function of beam current. Observation and analysis determine that this is an operational characteristic. However, further analysis must be performed for the case of a specific format since aspect ratio, raster size, number of scanning lines, repetition rate, etc. are independent variables that must be known to obtain a true prediction of tube performance in a particular application.

New projection tubes present a high brightness display. However this high-intensity energy is developed in an 18.75 square inch area. Even though up to 300 foot-lamberts or more can be measured after lens transmission, the energy is distributed over a display of up to 48 square feet in which case up to 10 foot-lambert incident brightness would be obtained. The reflected image from a screen is not going to be at all bright with present materials and components (refer to Section 2).

Radiation effects will cause browning of the type of glass used in the 7WP4. An 80-kilovolt accelerating voltage is employed for electron acceleration to obtain as high as possible brightness. Unfortunately this energy level generates x-rays, and faceplate browning does occur. Only a few hours of operation reduce faceplate transmittance, and tests indicate that light output may be halved in less than 200 hours of operation. Also considerable x-ray shielding must be provided to assure personnel safety.

The projection tubes and associated apparatus used in this study have not proved reliable. It appears that circuitry operating at an 80-kilovolt level is quite prone to arcing, ozone generation, and corrosion within cable connections. Constant maintenance is

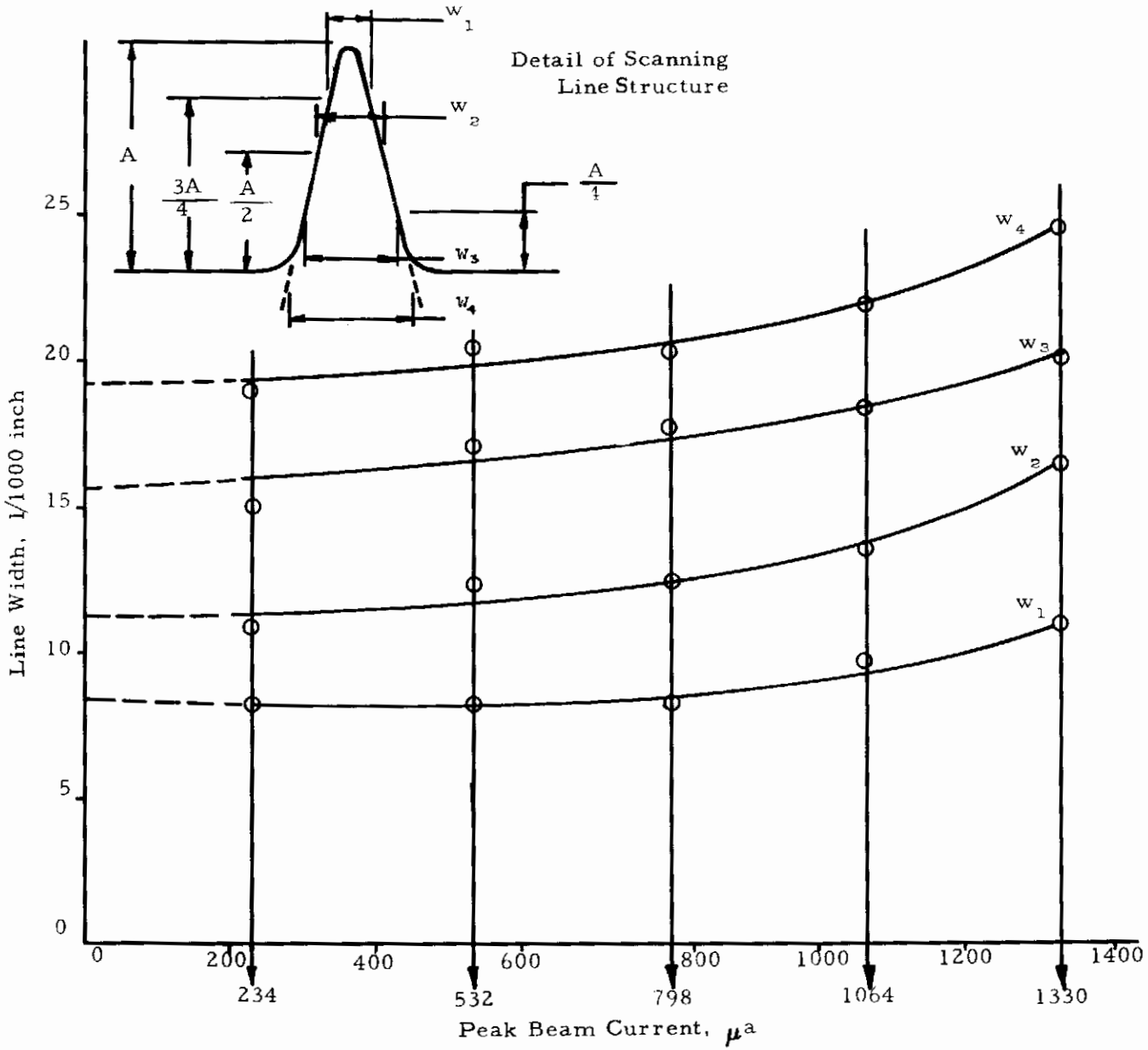


Figure 28. Scanning Line Width vs CRT Peak Beam Current

necessary to keep cables clean and arc-free, to keep tube cooling air clean and free of ozone, etc. One should not depend upon more than 40 hours of operation without maintenance of cables and air cleaners. The projection tube will be efficient for only about 100 hours, due to browning and resultant image tinting and dimming.

The specifications for 7WP4 projection tubes do not include resolution; thus no manufacturer's published prediction of performance is available. However a specific 5-inch by 3.75-inch "quality rectangle" is specified in which faceplate irregularities are controlled. Operation out of this region could provide areas of defocus in the display. Manufacturer's representatives predict a maximum 600-line resolution from the tube. This maximum is limited by the phosphor and beam spot sizes. The phosphor is a multi-layer arrangement, not an ordinary P4 surface. It contains beryllium, an element not considered desirable for ordinary tube use due to the danger of poisoning if the tube is fractured. The unusual thickness of this layer arrangement, necessary due to high velocity electron bombardment and resultant heat generation, contributes to a diffusion of light from back to front of the phosphor, resulting in a spot spread that is pronounced at higher brightness levels. Further spot size limitation is presented in the electron beam focusing that can be obtained with an 80-kilovolt acceleration at up to 2-milliamperes beam current.

To obtain the 600-line resolution in a 3.75-inch dimension, as indicated, the spot size must be 6.25 mils or less. It has been shown that this value can be obtained for low levels of beam current but at low contrast ratios, but cannot be obtained at ordinary operating levels.

SECTION 6

CONCLUSIONS AND RECOMMENDATIONS

The studies outlined in previous sections have yielded significant advances in the application of television displays. The development of a new quantitative method of display evaluation is most important, and represents a meaningful accomplishment. Conversion of the F-151 closed circuit television projector to 1029 scanning line television operation will provide an economical and convenient means for studying display techniques for images of up to 1000 line television resolution.

At the conclusion of the present contract the F-151 projection device is operational at 1029-line scanning rates, and has a 20 mc video driving amplifier. There has been no opportunity to fully evaluate the system at these rates; a signal source, a television camera system, has just been installed to permit such operation.

Displays at 525-line scanning rates have been presented through the 20 mc projection video amplifier. Visual analysis indicates a startling improvement in display quality; up to 700 lines resolution (at tube center) has been observed simultaneously with 8 shades of grey from the EIA Television Test Chart. The contrast ratio is reduced at higher resolutions; however, observations indicate that performance is better than that expected from the theoretical prediction of Section 5. Actual performance observed with the 1029 scanning line system, plus details of converting the projector from the conventional 525-line system to 1029-line operation will be covered in the report of Phase II.

The display must be evaluated by the method described in Section 4 to determine limits of actual system performance and to verify the predictions made from the original 7WP4 analysis of Section 5. It is also important to maintain the system, including television cameras, processing amplifiers, and display units at the peak of performance for the best evaluation and for satisfactory demonstration of system capability. Emphasis is placed on this portion of the operation because of the poor past history of reliability in the system used for this study, especially in the projection cathode-ray tube and 80 kilovolt supplies.

Maintenance of television systems is a complex task that is too often lightly regarded. As a result, most maintenance may be shunted to a technician with little or no related background. Only the obvious and catastrophic failures are repaired, and the system slides from peak performance gradually. This is evidenced by a loss of resolution and contrast, by the introduction of video streaking, overshoots, or poor transient response, etc. Texts and references do not discuss the recommended techniques which could be employed for system preventive maintenance, such as video amplifier sweeping, sweep linearity checking, video phase response testing, and so forth. A study and report on this as it applies to the Simulation Techniques Branch program would greatly aid not only this program but every Air Force group using television.

Note that the 7WP4 evaluation, presented in Section 5, is pessimistic regarding suitability of this tube for high resolution display use. The display device survey, Section 3, indicates that cathode-ray tube state of the art is limiting progress toward improved displays; the required light source intensity is not available in the tubes as the art is known today. Since methods of projection not employing tubes are undesirable (i.e. Eidophor, Light Valve), emphasis must be placed upon projection cathode-ray tube development and improvement. Novel approaches which circumvent the heat and browning problems in traditional glass-enveloped tubes have been outlined, and are considered worthy of investigation.

Because technical advances are allowing daily improvements in other types of display equipment, a continuing market survey and close liaison with closed circuit television manufacturers is strongly recommended. Progressive developments in light beam modulation devices and in thermoplastic display equipment are being pursued intensively. Logically, continuous follow-up is indicated in both these areas.

A precise method of evaluating display systems has been devised. No comparable method exists for evaluation of image pickup and processing equipment (camera chains). Development of such a technique should assume high priority, for the display device, no matter how precise, may well be limited by the signal input. Specifications for camera systems are vague and superficial enough to preclude prediction of actual performance. Consider resolution: while resolution may be specified, this is of

no value unless the contrast ratio establishing limiting resolution is also specified. Proper evaluation would consider all such interrelated parameters.

During formulation of the display evaluation method and study of cathode-ray tube effectivity, associated problems in image generation were uncovered. An item under current discussion for visual simulation use is a satisfactory procedure of star field generation. Previous studies indicate that computer generation is desired, as large physical models must be accommodated and controlled with other methods. A brief survey of scan conversion equipment now on the market shows that present devices are approaching 1000-line resolution with up to eight shades of grey. This equipment could be adapted to convert a computer-generated star field to television format in a modest development program.

The overall objective of this and similar studies is to provide a large area display of adequate fidelity and dynamic range for simulation training. Resolving power of the eye far exceeds even the 1000-line large area display. Therefore basic research is appropriate to increase the resolution capacity of a television system, through development of equipment with increased bandwidth. For instance, there has been preliminary consideration of camera tubes with 2000-line resolution, requiring a video channel of 40 mc bandwidth, twice that sought in this study. Traditionally the emphasis is placed on cameras and processing equipment; in this case primary emphasis must be placed upon a satisfactory display medium, as large area projectors present equal or greater challenges than pickup devices.

Finally, the consideration of color television as an aid in simulation training is a reminder that the problem area of color reproduction is as yet almost unattended. The present three primary color, three-channel system has not been accepted as a high quality, dependable data transfer medium. An improved approach to color reproduction must be developed if a high resolution color display is to be obtained within present or projected state of the art bandwidth.

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9. Goodyear Aerospace Corporation, Memorandum AP-105569, Bright Projection Screens and Projection Screen Structures, Goodyear Aerospace Corporation, Akron 15, Ohio, undated.

Specific Citations

Camera Tubes

See Chapter 5 of Ref 2
See Chapter 4 of Ref 3

Definitions

See pp 1-36 thru 1-65 of Ref 2
See pp 617-618 of Ref 3

Display Tubes

See Chapter 5 of Ref 2
See Chapter 5 of Ref 3

Screens

See Ref 7
See Ref 8
See Ref 9

Standards

See pp 2-2 to 207, 2-20 to 2-25, and 2-47 to 2-54 of Ref 2
See Chapter 12 of Ref 3

TV Systems, Signals, and Waveforms, Devices

Chapters 5, 8, and 10 of Ref 2
Chapters 1 and 15 of Ref 3

PHASE II

SECTION 1

INTRODUCTION

Visual simulation of hypothetical conditions or observed objects requires realism. For this purpose, the use of a projected television image requires, by necessity, good contrast and high resolution capabilities. The object is to present a television picture simulating the resolution and contrast qualities of an actual scene or at least of a high quality photograph.

The F-151 Gunnery Trainer CCTV and projector system, which operates at a normal 525 lines per frame horizontal scanning rate, is capable of resolving approximately 400 lines at the center of the image, with a grey scale of eight shades. However, due to the large size of the projected image, visual perception of the horizontal scanning lines is quite noticeable, and detracts from the desired photographic effect.

In an effort to minimize the effect of visual perception of the horizontal scanning lines, and thus increase the photographic qualities of the projected image while maintaining the same image, the use of a greater number of scanning lines was the logical solution.

By increasing the number of horizontal scanning lines and maintaining the same vertical image size, each line would be reduced in width, and the spacing between each line would be less. As a result, it becomes much more difficult for the viewer to perceive the presence of these lines, and the quality of the image is improved considerably.

SECTION 2

METHOD OF APPROACH

The presentation of a projected image at a scanning rate higher than 525 lines per frame, presented several questions:

1. What new scanning rate should be used?
2. What modifications of the present system would be required?
3. By what method should these modifications be accomplished?

Obviously, to present a television image, a television camera is required. Likewise, for CCTV systems, a sync generator is also required to provide the system with recurrent trigger pulses having the proper time relationship. It was desirable to obtain a commercial CCTV system for the source of signals. It was found that a commercial CCTV system with a horizontal scanning rate of 1029 lines per frame, and a frame rate of 30 frames per second was available to the Simulation Techniques Branch. With this data, it could now be determined what modifications would be necessary to operate the F-151 Gunnery Trainer at these rates.

The normal interlaced 525-line system, operating at a rate of 30 frames per second, requires a horizontal scanning frequency of 15.75 kc and a vertical scanning frequency (field rate) of 60 cps.

The interlaced 1029 lines per frame system, also operating at 30 frames per second, requires a horizontal scanning frequency of 30.87 kc and a vertical scanning frequency of 60 cps.

It can be seen then that the F-151 Gunnery Trainer projector must be modified to be capable of operating at the higher frequency for horizontal scanning required for a 1029 lines per frame presentation. The modifications required to provide this capability of operation presented two avenues of approach. The basic television electronics of the F-151 Gunnery Trainer could be modified to operate at this higher frequency, or new circuitry could be designed and developed for this purpose, and new chassis fabricated. Since a 1029-line camera system was available to the Government, redesign of the entire camera system did not appear to be practical.

It was desirable that the 525-line system of the F-151 Gunnery Trainer be left intact and operable for purposes of further evaluation. This also meant that operational comparative criteria could be obtained as required during the development phase of the 1029-line system. Therefore, the modification requirements were that either mode of operation could be obtained with a minimum of time required to make the necessary changeover electrical connections. It was further indicated that, should the 1029-line system prove to be capable of providing the desired display, the 525-line system might be dismantled and removed from the equipment room. The remaining 1029-line system components would require much less space than would the 525-line system.

The method of approach was to design, develop, and fabricate the necessary new circuitry for the 1029-line projector. The fabrication of the 1029-line equipment would be such that either system could be operated independently and allow the removal of either capability without causing the remaining system to be inoperable.

SECTION 3

TECHNICAL DISCUSSION

The basic block diagram for the elctronic circuitry of the F-151 Gunnery Trainer CCTV and projector system is shown in Figure 1. In order to simplify the design and development problem of the 1029-line system, this basic system structure was retained. As a result, a number of circuits could be duplicated according to the schematic diagrams of the original 525-line system rather than redesigning them. However, the chassis size requirements were more stringent in order to obtain a more economical fabrication of these subsystem units. Existing power supplies were utilized but were remounted to take up less space in the overall system. Those circuits shown in Figure 1 that were duplicated are:

1. Vertical Sweep Generator
2. Sweep Protection
3. Projector Control

A system of 1029-line CCTV equipment, consisting of cameras, monitors, and a sync generator, had been obtained by the Government. This equipment was integrated into the 1029-line projector system shown in the block diagram of Figure 1.

The 1029-line CCTV system has, by nature of the design, the potential of resolution approaching 1000 lines. To fully utilize this potential, a new video amplifier was required. This amplifier had to have a sufficient band width to pass the video spectrum of 1000-line information. The required band pass was calculated to be 20 mc. With this information and other operational criteria, Dage Division of Thompson-Ramo Woolridge developed and fabricated an amplifier capable of driving a 7WP4 cathode-ray tube.

The projection CRT of the F-151 Gunnery Trainer utilizes electromagnetic principles to attain deflection of the electron beam. This means that a current, passed through an electromagnetic deflection yoke which encircles the neck of the CRT, must increase linearly to provide a linear deflection of the CRT electron beam. This current must then decrease rapidly to the initial value in order to allow the electron beam to return to its starting point in as short a time as possible. This current, if observed on an oscilloscope, would appear in the shape of a sawtooth as shown in Figure 2, and is commonly termed the sweep current. The primary problem of the 1029-line system was to pass a linear sawtooth current through the horizontal winding of the deflection yoke at a rate of 30.87 kc, and yet achieve a sufficiently rapid beam return.

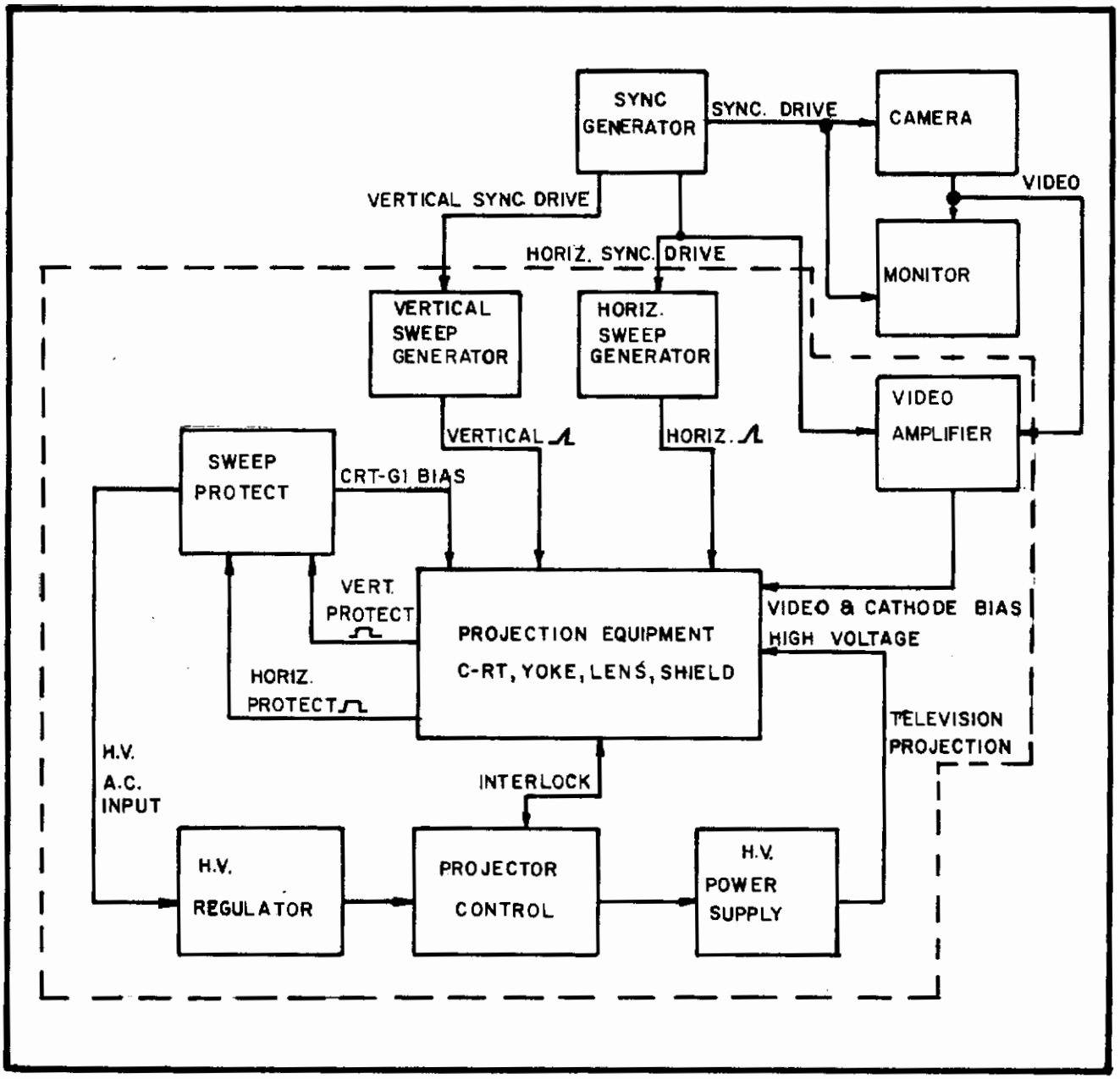


Figure 1. Basic Block Diagram of CCTV and Projector System

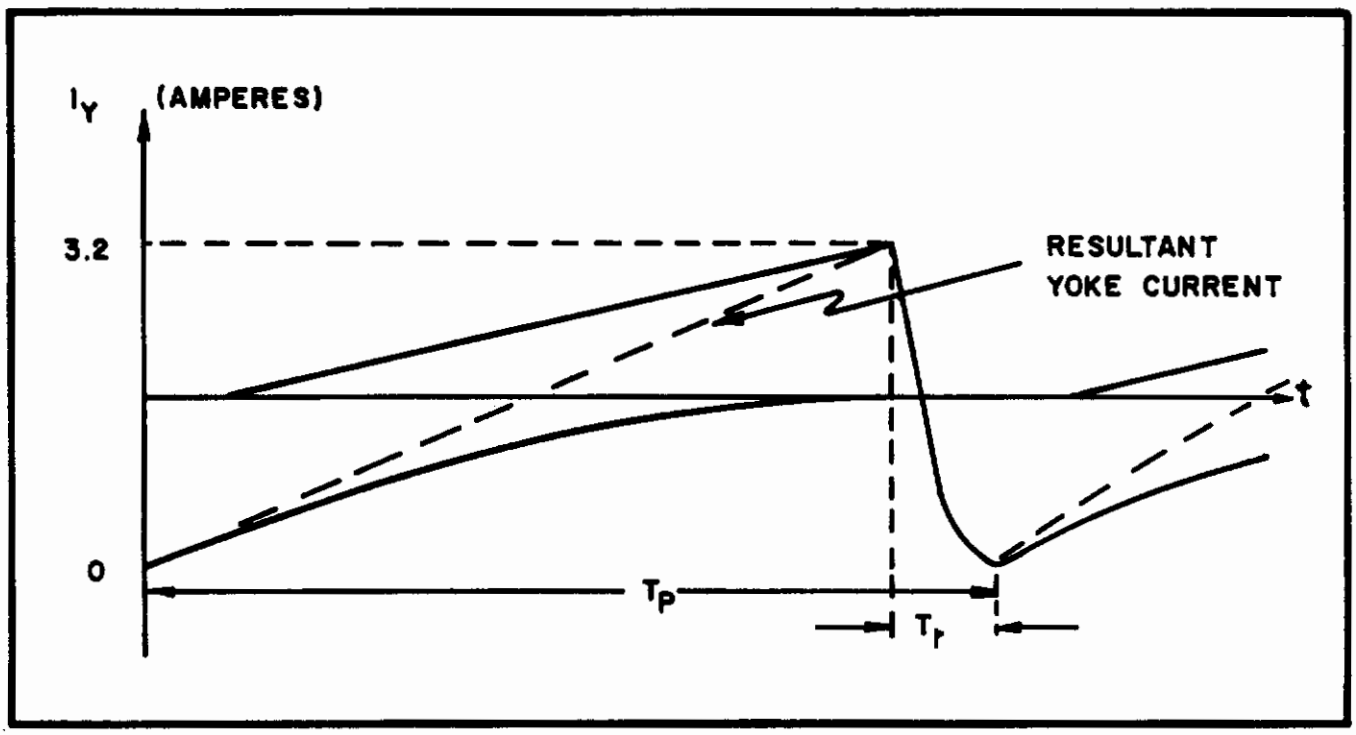


Figure 2. Sweep Transformer Output Current

The time required for the excursion of the electron beam of the CRT from its starting point, across the face of the CRT, and return to its original starting point, is defined as its period and is expressed by equation:

$$T_p = \frac{1}{f}$$

where T_p = seconds

f = frequency

For the horizontal deflection of the electron beam in the 525-line system, this time is:

$$T_p = \frac{1}{15.75 \times 10^3} = 63.4 \text{ microseconds}$$

The time required for the electron beam of the CRT to return to its starting point from the point of maximum deflection is defined as its retrace time, t_r. (See Figure 2.) For the horizontal deflection in the 525-line system, this time is approximately 7 microseconds, about 11% of the total period.

In the 1029-line system:

$$T_p = \frac{1}{30.87 \times 10^3} = 32.4 \text{ microseconds}$$

$$t_r = .11\ (32.4 \times 10^{-6}) = 3.5 \text{ microseconds}$$

In the 525-line system it was observed that a sawtooth current of 1.6 amperes peak-to-peak occurring at a rate of 15.75 kc was required to obtain the maximum horizontal size of the projected image. The parameters of the horizontal winding of the deflection yoke were known to be 2.84 millihenries inductance and 2.35 ohms resistance. Thus, for the 1029-line system the peak power requirement of the horizontal sweep generator, necessary to drive this deflection yoke winding, could be calculated from the equation:

$$P = \frac{1}{2} LI^2{}_p F + I^2{}_p R$$

P = watts

L = henries

I_p = amperes

f = frequency

R = resistance

$$P = \frac{1}{2}(2.84 \times 10^{-3})(1.6)^2(30.87 \times 10^3) + (1.6)^2(2.35)$$

$$= 112.5 + 6 = 118.5 \text{ watts}$$

The peak voltage developed across the deflection yoke does not occur during the linear portion of the current sawtooth waveform, but rather occurs as a result of the rapid change of current in the flyback interval. The development of this voltage is the result of the transient effect of the rapid change of the deflection current to zero during retrace. This voltage, commonly termed the flyback voltage, can be generally expressed by the equation:

$$e = L \frac{di}{dt}$$

where

e = volts

L = henries

di = change in current in amperes

dt = time required for current change in seconds (t_r)

In the 525-line system:

$$e = 2.84 \times 10^{-3} \frac{(1.6)}{(11 \times 10^{-6})} = 413 \text{ volts}$$

In the 1029-line system, this voltage will be much greater:

$$e = 2.84 \times 10^{-3} \frac{(1.6)}{(3.5 \times 10^{-6})} = 1300 \text{ volts}$$

Noting the great difference in flyback voltage theoretically developed in the two systems, indications were that the large voltage developed in the 1029-line system operation would exceed the rating of the insulation breakdown voltage of the deflection yoke.

Further research into the problem was required. In looking at the physical construction of the yoke, it was found that the horizontal deflection coils of the yoke consisted of two identical windings connected in series by means of external wiring. This type of construction might allow a parallel coil connection, thereby providing more feasible characteristics of operation.

The amount of inductance of the windings connected in parallel would be reduced to one-quarter of the original value. However, the amount of current required to provide the same maximum horizontal size of the projected image would be twice as great, or 3.2 amperes peak-to-peak. The new parameters of the yoke for this configuration were found to be 0.71 millihenries inductance and 0.59 ohms resistance.

The amount of flyback voltage that theoretically should be developed can now be calculated:

$$e = L \frac{di}{dt}$$

$$e = .71 \times 10^{-3} \frac{3.2}{3.5 \times 10^{-6}} = 650 \text{ volts}$$

This value is still larger than that of the 525-line system operation, but is only half that required with the series windings. The peak power requirement can also be calculated:

$$P = \frac{1}{2} LI^2{}_p f + I_p{}^2 R$$

$$= \frac{1}{2} (.71 \times 10^{-3}) (3.2)^2 (30.87 \times 10^3) + (3.2)^2 (.59)$$

$$= 112.5 + 6 = 118.5 \text{ watts}$$

Since the peak power requirement is the same as before, the parallel yoke configuration indicates a practical mode of operation, with a greatly reduced probability of breakdown due to flyback voltage.

The deflection yoke used in the 525-line system was manufactured by Syntronic Instruments Corporation. In order to verify the above conclusions, the problem was presented to their personnel. From their original design calculations, they determined that a parallel connection of the two windings of the horizontal deflection coils is feasible; the only other alternative would be to have a new yoke designed, which would be impractical from the economic standpoint. This alternate solution will not be completely discarded, however, until the results of actual operation of the 1029-line system warrant further assurance in this area.

The signals delivered to the horizontal winding of the deflection yoke from the horizontal sweep generator are transformer coupled. Operation at 30.87 kc required a new transformer, regardless of the deflection yoke configuration. However, design parameters for the transformer, by necessity, had to be determined after the deflection yoke configuration was resolved in order to design for maximum power transfer. This new transformer was designed and fabricated to operational specifications.

The horizontal sweep generator was breadboarded and used to drive a load which simulated the parameters of the horizontal winding of the deflection yoke. The transformer had to be redesigned due to the fact that insulation breakdown occurred from the flyback voltage. When this problem was solved, the new sweep generator yielded satisfactory results.

The vertical sweep generator was duplicated according to the original schematic, because the 525-line system and the 1029-line system both operate at 30 frames per second. Likewise, no modifications of the vertical winding of the deflection yoke were required.

When fabrication of the 1029-line subsystem units was completed, interwiring of the units was begun. The most difficult portion of this task was the utilization of a proper interlock arrangement. The purpose of the interlock system is to render the projection CRT inoperative when necessary to protect the face of the CRT from damage as a result of a failure elsewhere in the system. A thorough knowledge of the 525-line system operation was required to attain this degree of system operation and performance. With the aid of the original 525-line system schematic diagrams, and additional simplified diagrams made after tracing out numerous interconnecting circuits, the 1029-line system interlock arrangement was designed. Upon completion of the interwiring of the 1029-line subsystem units, the effectiveness of the interlock arrangement was checked by means of generating intentional failures and monitoring voltage levels at critical points in the system. The interlock checkout was performed without the high-voltage power supply being on. Permanent damage to the face of the CRT will result whenever high voltage is applied to the CRT anode without proper beam deflection; the interlocking arrangement prevents such occurrence.

SECTION 4

SUMMARY AND CONCLUSIONS

The projection system in the Flight Simulation Television Laboratory has been converted from the "conventional" 525-scanning line format to a 1029-scanning line arrangement. The video processing channel has been upgraded from less than 5 mc to almost 20 mc. This implies that the system could display television data up to 1000-line resolution, providing the projection cathode-ray tube has the basic capability for presenting such displays.

It is felt that exact evaluation of tube capability, an enigma of long standing, has been solved by the development of a new evaluating technique. The new method employs signal detection by a secondary television camera, thereby analyzing the image in terms of signal data rather than in subjective visual appraisal. A prediction of 7WP4 operation in a 1029-line mode was made from evaluation data.

A 1029-line display was presented from the 7WP4 tube. This display, the product of research apparatus, exhibited some imperfections, the most noticeable of which was sweep nonlinearity in both the horizontal and vertical directions. Even so, inspection of the raster and display presented factors that are inconsistent with the predictions. Presentation of sharp, individual scanning lines was not expected, since the evaluation suggested only a merged, continuous, and nondetectable pattern of lines above a 700-line raster. Yet the raster was sharp, well focused, and clear. The limiting horizontal resolution was observed at about 700 lines; the prediction was that virtually no contrast would exist at this point. And, rather than no contrast, an appreciable contrast was observed even at the limit of resolution.

Little is known about the true quality of the display generation system. It was a 1 1/2 inch vidicon camera system obtained for the Air Force through a development contract with Bell Aerosystems. The system was received after the projector conversion contract was completed, and therefore no simultaneous testing or integration effort could be applied.

A most significant question has been raised by observation of the F-151 projector operating at 1029-scanning line rates. A prediction of performance of the 7WP4 tube indicated a limit of approximately 650 lines resolution. The horizontal resolution was found to be at or near this limit in the high-quality system. However, the scanning lines in the vertical dimension were distinctly separable, which was not expected. The raster format contains in the order of 980 active scanning lines, so the raster structure was expected to be a merged mass of brightness rather than a well defined line. Thus, an evaluation of the tube operating at 1029 scanning lines, using the same technique as that used previously, would pinpoint the variance. This variance could be caused by a different 7WP4 spot size under the new conditions, by drastically different beam current levels, or perhaps even by an oversight in the prediction derived in the earlier evaluation. The cause must be identified to validate the evaluation technique and the predictions.

The evaluation technique developed in previous research studies uses the basic scanning line and a white raster as the media for analysis, a universal method adaptable to all formats. The areas of greatest interest in the test runs are the width of a scanning line, the behavior of the scanning line under various conditions of beam current, and the apparent contrast obtained from a number of different line spacings. A second analysis may reveal variations from the predicted performance, for the basic scanning line may be different for the 525- and 1029-line modes. Because the scanning speed is different, the line width may be significantly altered. It is reasonable to expect that the higher scanning speed of the 1029-line format may yield a narrower line, explaining why the raster with higher line count is well defined rather than presenting a merged, undefined pattern without observable scanning lines, as predicted.

An equally important consideration is setting up of the entire television system (including cameras, processing equipment, and monitors), providing proper interconnections, and integrating the individual units into a fully compatible system. Particular emphasis must be placed upon proper setup, adjustment, and operational control to insure that the cameras are providing signals of full fidelity, and that both monitors and the projector are capble of equal fidelity in signal processing circuits. Only after this is done can a true evaluation of the projection tube begin with full assurance that all possible contributing elements are not falsely limiting performance. It was not possible to determine this in previous work, since camera equipment had not arrived until the concluding work on the program was in process. The 1029-line cameras must be properly and exactly set up for both the optical and electrical parameters. This determines especially the size of

image presented on the faceplate of the camera tube and the area of photoconductor being scanned. Both of these factors are critical in producing a signal with proper fidelity, and ironically are the items most prone to misadjustment or drift. The size of the optical image is difficult to determine, since distance-to-scene and lens distance to the camera tube face are critical.

The studies performed with the tube in this new format may well dictate changes to the evaluation method and to subsequent analysis. One area quite likely to be changed is the consideration of scanning speed in the use of measured line width, especially if operation in another format is to be predicted. Another important aspect to be verified is the relationship of brightness, beam current, and scanning speed. Scanning speed will also affect the phosphor output (brightness). It is expected that the faster the scan, the less brightness that can be obtained from a given CRT screen area. The evaluating technique assumes that this is a direct relationship; measurements must be made to prove the assumption true.

It is of great advantage to have a reference display other than the projected image. Standard television monitors can provide this reference, but they must be accurately adjusted and aligned to act as a reference standard.

The original F-151 Gunnery Trainer 525 line CCTV control equipment consumed approximately 144 cubic feet of space (see Figure 3). Approximately half of this equipment was redesigned and repackaged to consume only 32 cubic feet of space (see Figure 4) for the 1029-line CCTV system.

The interconnecting cabling between the 525-line system and the 1029-line system is such that to change from one mode of operation to the other requires the changing of only four cable connections and two switch positions (see Figure 5). The time required to make this changeover should be no more than 15 minutes, assuming the CCTV snyc generators and cameras are already connected properly into the system. These units do not have to be disconnected for operation in either mode. Thus one of the fundamental design criteria was fulfilled, this being that either mode of operation could be obtained with a minimum of time required for the necessary changeover electrical connections.

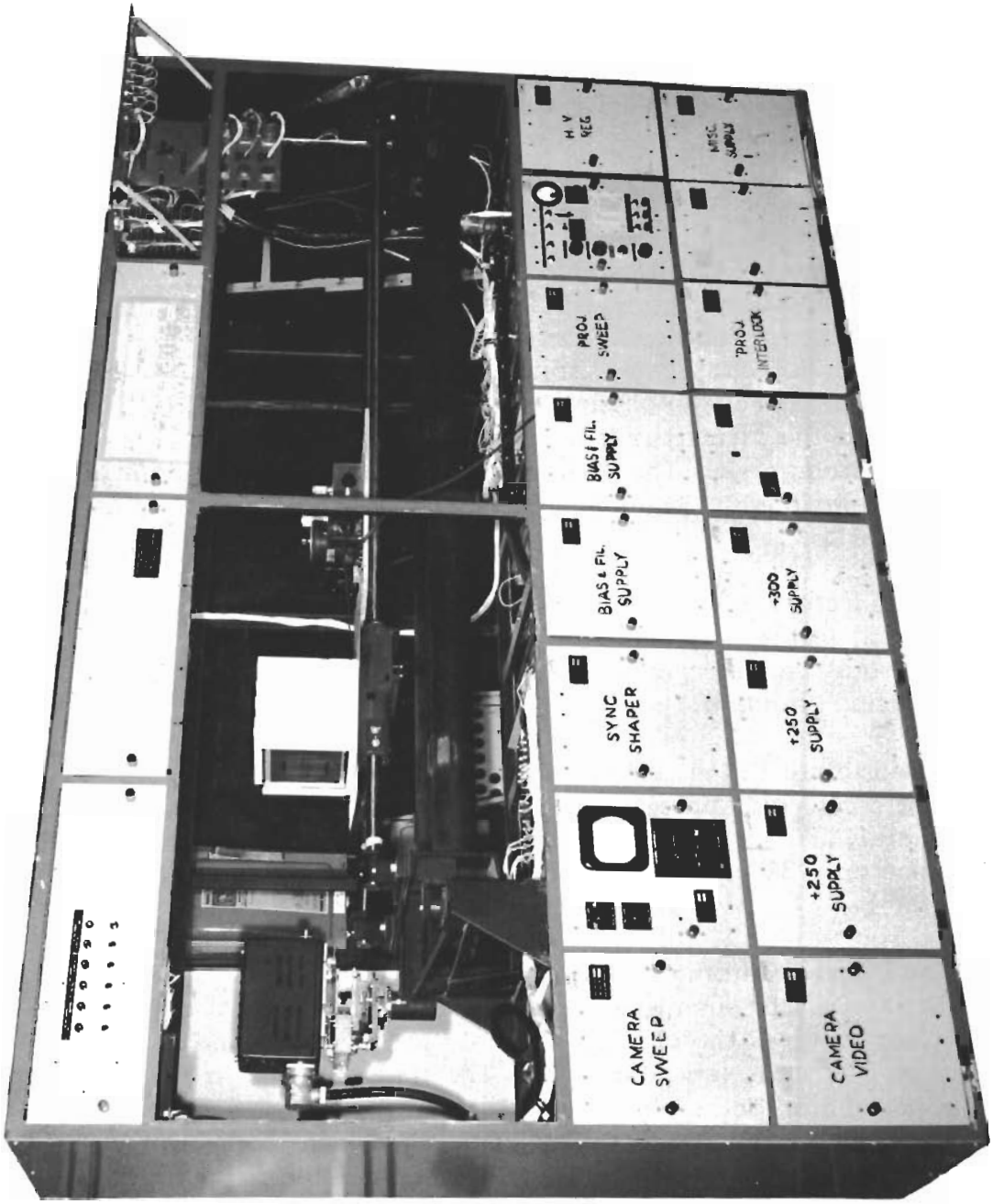


Figure 3. 525-line CCTV Control Equipment Rack

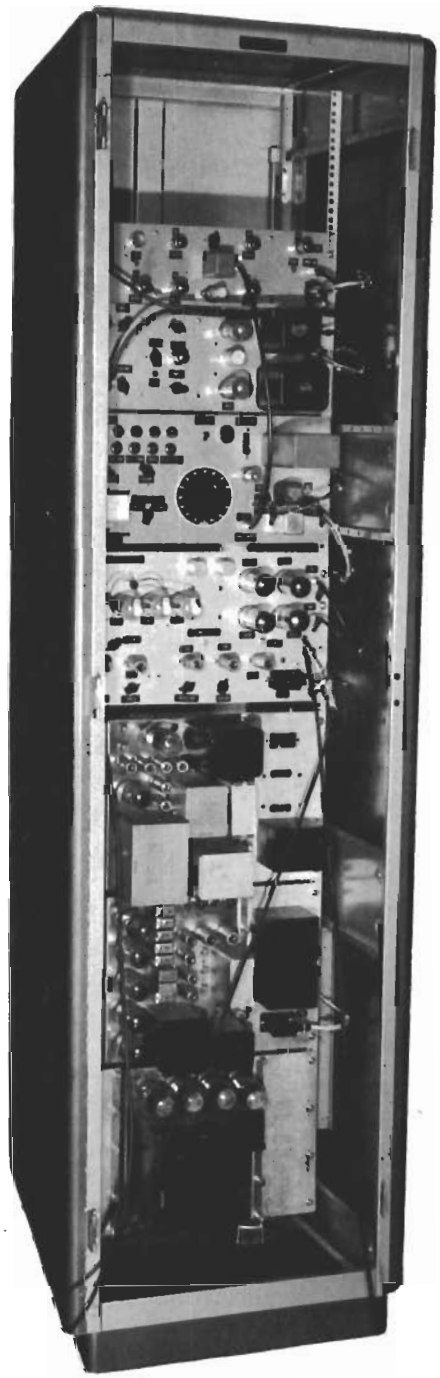


Figure 4. 1029-line CCTV Control Equipment Rack

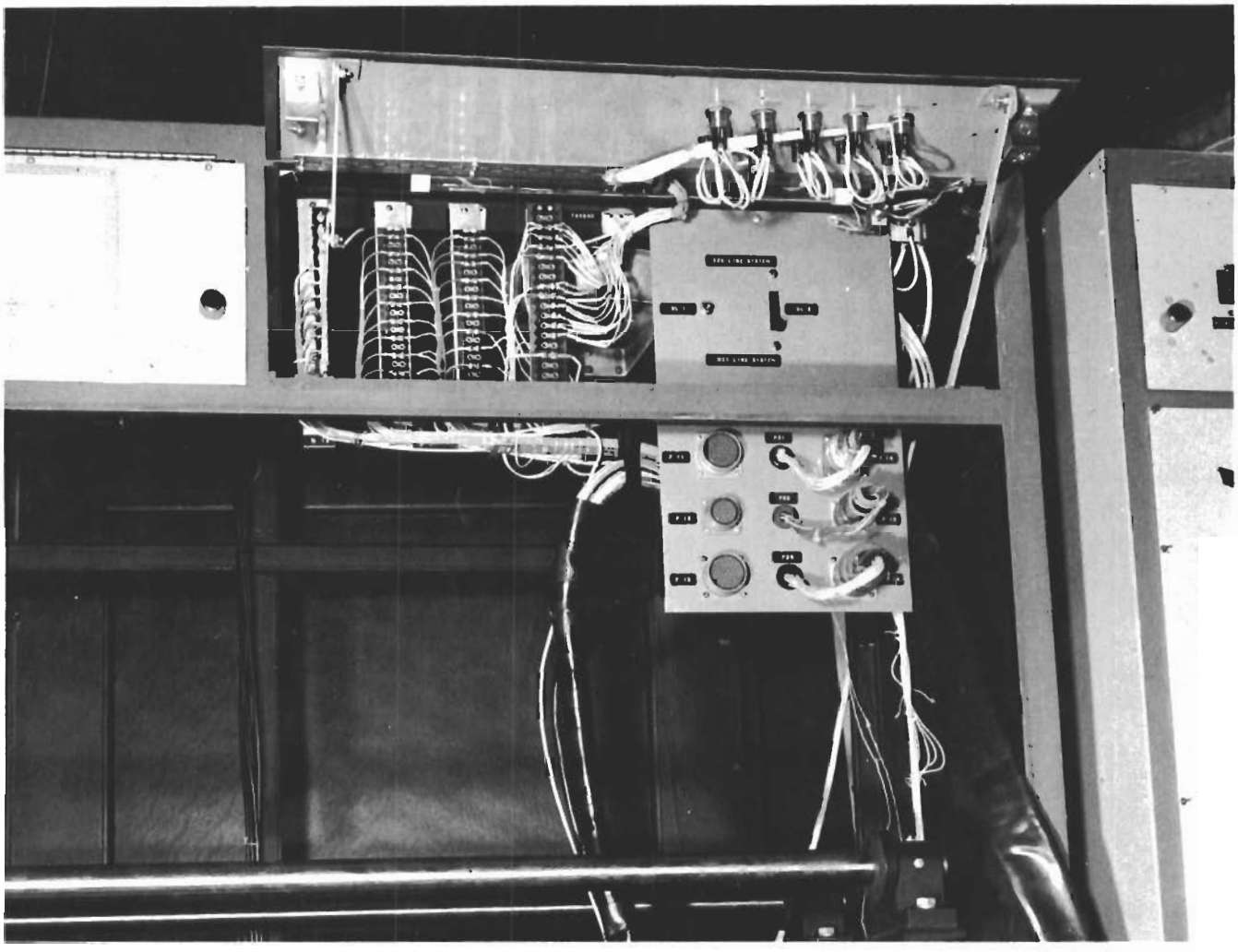


Figure 5. Junction Panel

CONCLUSIONS

The research conducted in this program presents rather startling results. The 7WP4 projection tube performance obtained in the 1029-line mode exceeds that which was predicted. The performance limitations set forth by the manufacturer and by the tube evaluation in a 525-line format apparently have been exceeded. The degree to which the specifications have been extended will not be known until further tests are performed. These tests will require a presentation in a 4 x 3 aspect ratio rather than the 1 x 1 aspect ratio used for the previous evaluation; the camera equipment format, which governs system operation, was not known when this initial 7WP4 evaluation was performed.

Observation of the display obtained at the conclusion of the contract indicated that limiting horizontal resolution will be at 650 to 700 lines, within the range of prediction. However, the well defined vertical raster, observed at 1029-line operation as well as 525-line operation, was not expected. Further study into basic tube characteristics must be performed to describe the behavior of cathode-ray devices under various operating conditions. Specific publications in this area have not been found, though surely this has been investigated by those developing tubes. It was indicated that the 7WP4 and other projection tubes have been fabricated for 525-line use, and testing at other scanning rates has not been of interest.

These events indicate that a research program into basic CRT characteristics is in order, especially for the projection devices. This study must be carried into faster scanning rates, such as 2 μsec per inch of display surface, which are encountered in the high quality, 1029- and 1203-line systems. It is likely that CRT spot size behavior and brightness output have not been studied at these rates. Such an investigation will provide significant insight into the ultimate capability of display-tube performance. The television industry does not have such knowledge regarding its products at the present, as evidenced by the results of this research program. However a continuation of this effort can establish quickly the ultimate performance obtainable from modern CRT devices.

PHASE I

APPENDIX I

VERTICAL DEFLECTION DATA

The analytic technique is keyed to 7WP4 vertical deflection size since this was varied to change the information density represented by adjacent scanning lines (see Section 4). An accurate measure of vertical deflection size (which controls raster size at the 7WP4 screen) was therefore required.

A convenient method of monitoring vertical deflection is to measure deflection current in the deflection coils, which is accomplished by monitoring voltage across a known resistor (R5271) placed in series with the coils, as shown below:

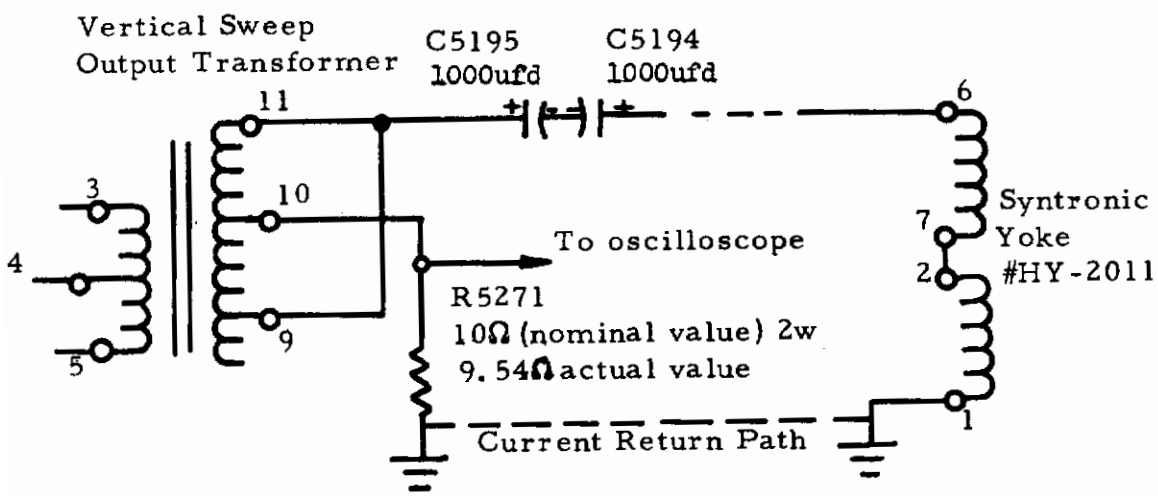


Figure 29. Circuit Arrangement for Measuring Vertical Sweep Current in the F-151 Gunnery Trainer Closed Circuit Television System

The current is then found by application of Ohm's law,

$$I = \frac{E}{R} = \frac{E \text{ measured}}{9.54\Omega} \text{ (amperes)}$$

The actual resistance value of R5271 was measured on a Wheatstone Bridge.

The data obtained in this manner are shown in Table 3 and plotted in Figure 30. They may be correlated with data obtained in subsequent tests.

Table 3

VERTICAL SWEEP SIZE

Picture Height CRT Face, in.	Voltage Sawtooth Across 9.54Ω**, v	Current Sawtooth through Yoke, ma
2.25	2.5	262
2.5	2.6	272
3.0	3.2	335
3.5	3.6	377
3.75*	3.8	398
4.0	4.0	420
4.5	4.8	505
5.0	5.2	545
5.5***	5.4	568
6.0***	6.0	630

* 3.75 in. is normal picture vertical dimension (manufacturer's specification)

** Sweep linearity adjusted for linear presentation at each size measured

*** CRT face not marked above 5-in. size; 5.5 and 6-in. readings are estimated values

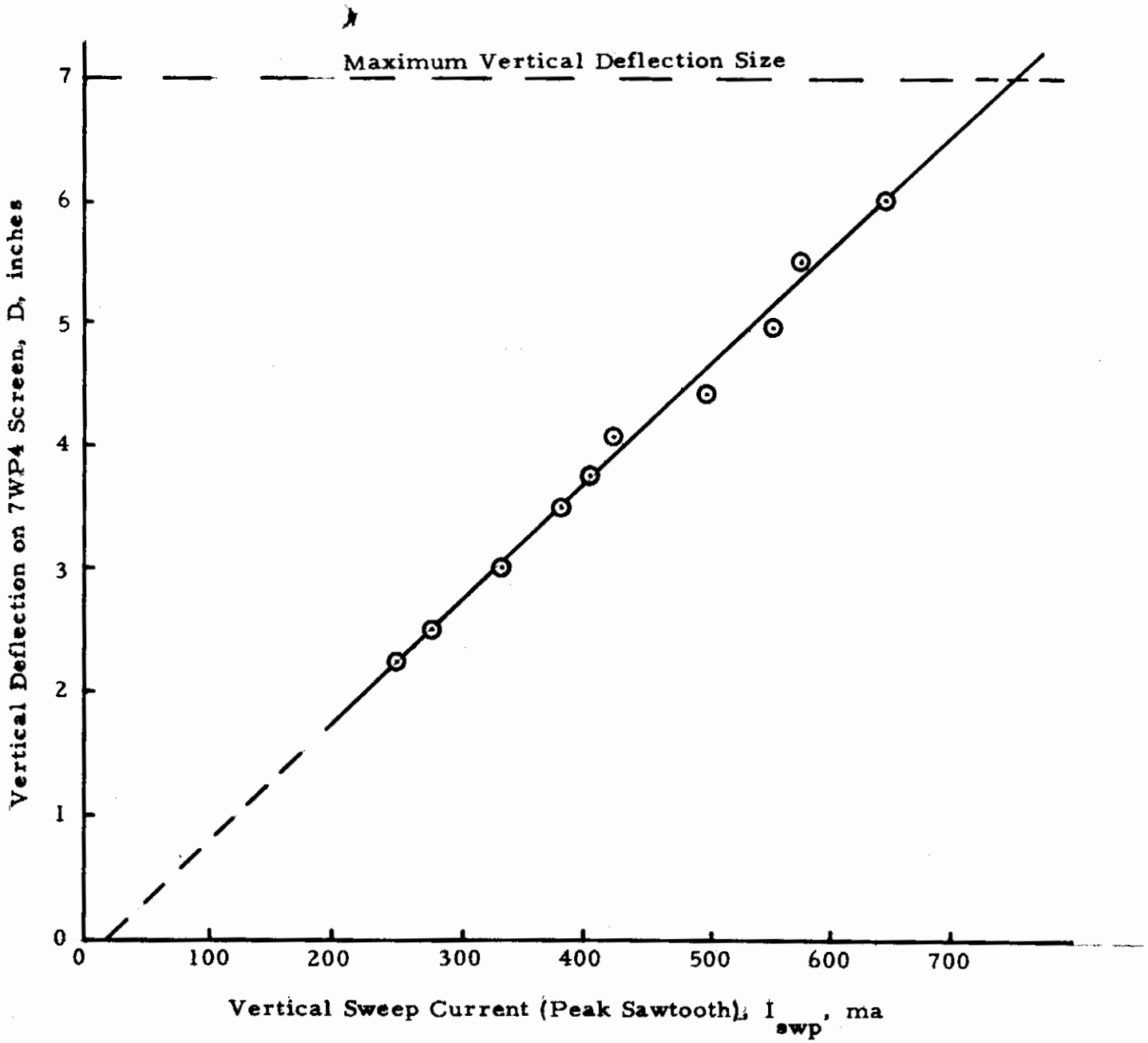


Figure 30. Vertical Raster Size vs Vertical Sweep Current 7WP4

PHASE I

APPENDIX II

BEAM CURRENT ANALYSIS

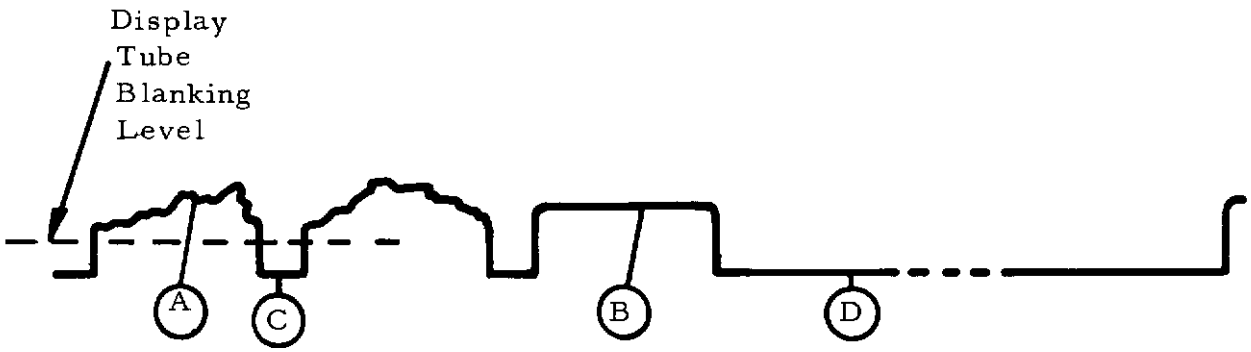
In the analysis it is necessary to use peak (or instantaneous) values of beam current when discussing cathode-ray tube phosphor brightness (see Section 5). The average current is obtained by conventional measuring methods, for example, with the meter used in the cathode-ray tube cathode circuit as shown in Figure 12. This average current is composed of the signal information plus a series of blanking pulses. The resulting complex waveform (see Figure 31) must be mathematically evaluated to determine the exact peak instantaneous current value.

The following conditions were established for the analysis:

1. Beam current is completely blanked off during the blanking interval, and no current flows during these periods. These facts were confirmed; no retrace lines were visible on the projected image as would have been the case if there had been energy flow during the blanking interval (see Figure 13).

2. The display is always a flat white field. Photographs, Figures 13 (c), (d), (e), and (f) confirmed this. (The transients at the beginning of the field are neglected.)

3. The rise time from beam off (blanked condition) to beam on is considered instantaneous. This was verified by the good pulse rise times shown in Figures 13 (a) and (b).



(A) Typical signal with video information during a scanning line

(B) Typical signal with all-white raster, as used in analysis

(C) Horizontal blanking interval

(D) Vertical blanking interval

Figure 31. Typical Beam Current Waveform

FORMAT A

To calculate the average-current to peak-current conversion factor for the 525-line system with 2:1 interlace and 60 cps field rate, we note that

$$N = L - \frac{t_v}{T_H} = 262.5 - \frac{1.36 \cdot 10^3}{63.4} = 262.5 - 21.5 =$$

241 active lines/field

and $$T_a = T_f - N t_H - t_v$$

$$T_a = \frac{1 \cdot 10^6}{60} - (241)(13.6) - 1.36 \cdot 10^3 \ \mu\text{sec}$$

$$T_a = 16,667 - 3280 - 1360 = 12,027 \ \mu\text{sec/field}$$

$$T_a I_p = T_f I_a \text{ (representing charge/field)}$$

$$I_p = \frac{T_f I_a}{T_a} \quad \text{or } I_p = \left(\frac{T_f}{T_a}\right) I_a$$

and it is shown above that $T_a = T_f - Nt_H - t_v$

$$\therefore I_p = \left(\frac{T_f}{T_f - Nt_H - t_v}\right) I_a$$

where T_f = time/field

T_a = active scanning period; time/field less horizontal and vertical blanking

I_a = average beam current at CRT cathode

I_p = peak beam current, to be calculated

t_H = horizontal blanking time } measured data, see Figure 32

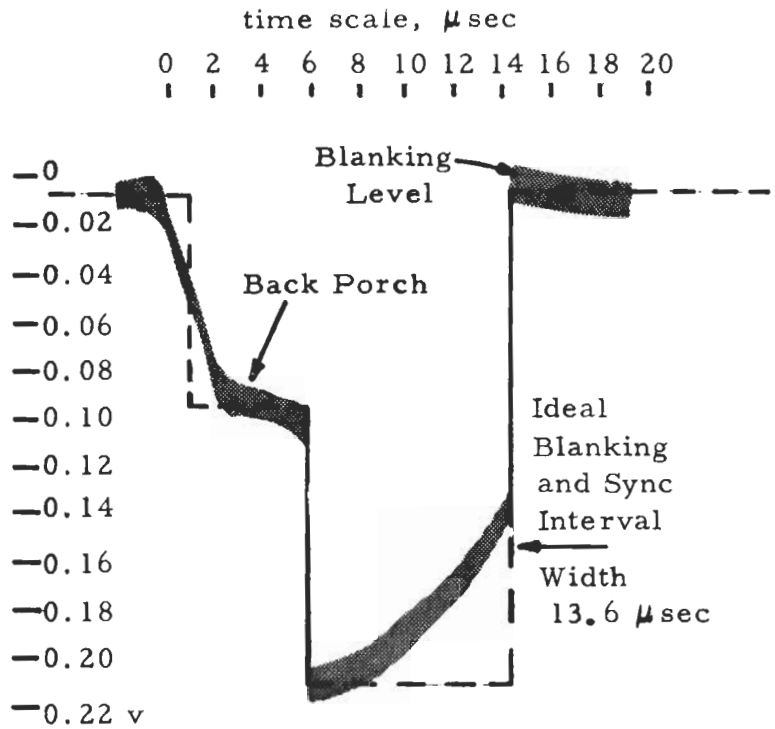
t_v = vertical blanking time

T_H = time for each horizontal line

N = number of active horizontal lines/field

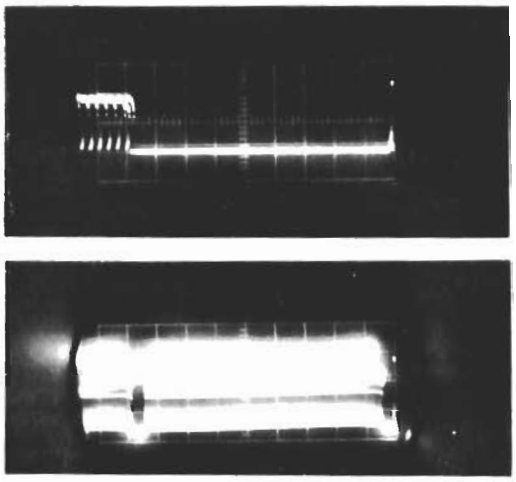
L = total number of scanning lines/field

An individual horizontal line of video showing detail of blanking and sync signal.



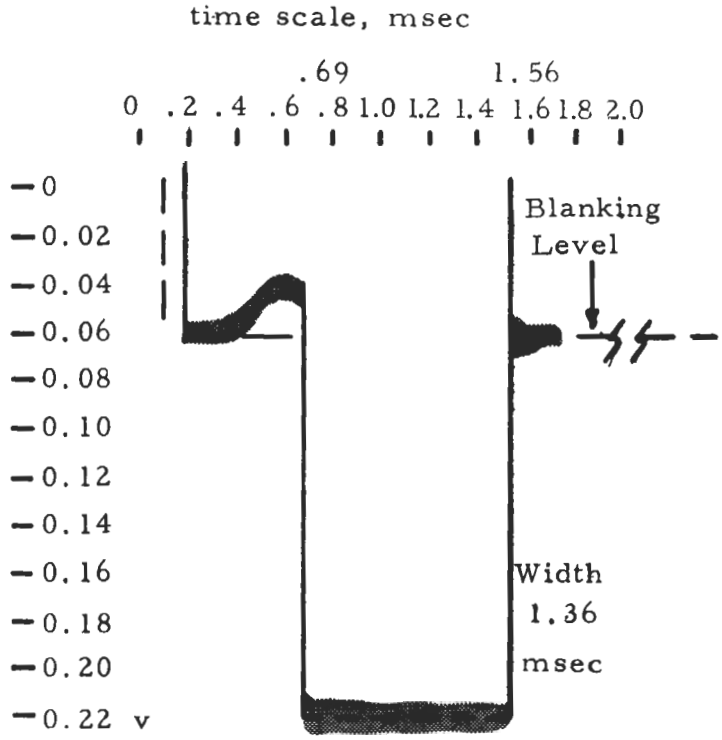
The widest portion is blanking; the narrow portion is sync drive.

a. Horizontal Blanking, 525 Line System



Detail of vertical blanking and sync interval. (top)

Display of the vertical deflection interval of 16,667 μsec.



b. Vertical Blanking, 525 Line System

Figure 32. Blanking Interval Waveforms

Case I

The derivation of the conversion factor for current flow during two fields/frame, as generally displayed, is

$$I_{p_1} = \frac{T_f}{T_a} I_a = \frac{16,667}{12,027} I_a = 1.39 I_a$$

and inversely,

$$I_a = \frac{T_a}{T_f} I_p = \frac{12,027}{16,667} I_a = 0.722 I_p$$

Case II

The derivation of the conversion factor for current flow only during one field/frame, a special case in which every other frame has no current flow, the charge per frame is represented by

$$T_a I_{p_2} = 2 T_f I_a$$

$$I_{p_2} = \frac{2T_f}{T_a} I_a$$

$$I_{p_2} = 2 (1.39) I_a = 2.78 I_a$$

FORMAT B

For a 1029-line system with 2:1 interlace and 60-cps field rate, with the assumed values per the analysis, and displaying two frames/field

$$T_f = 1/60 = 16,667\ \mu\text{sec}$$

$$t_h = 5\ \mu\text{sec}$$

$$t_v = 43 \text{ lines} = 43(32.4) = 1390\ \mu\text{sec}$$

$$N = \frac{1029}{2} - 43 = 514.5 - 43 = 471.5 \text{ lines}$$

$$T_H = \frac{16,667}{514.5} = 32.4\ \mu\text{sec}$$

Then

$$T_a = T_f - Nt_H - t_v = 16,667 - 471.5\,(5) - 1390$$

$$= 16,667 - 3745 = 12,922\ \mu\text{sec}$$

and

$$I_a = \frac{T_a}{T_f}\ I_p = \frac{12,922}{16,667}\ I_p = 0.775\ I_p$$

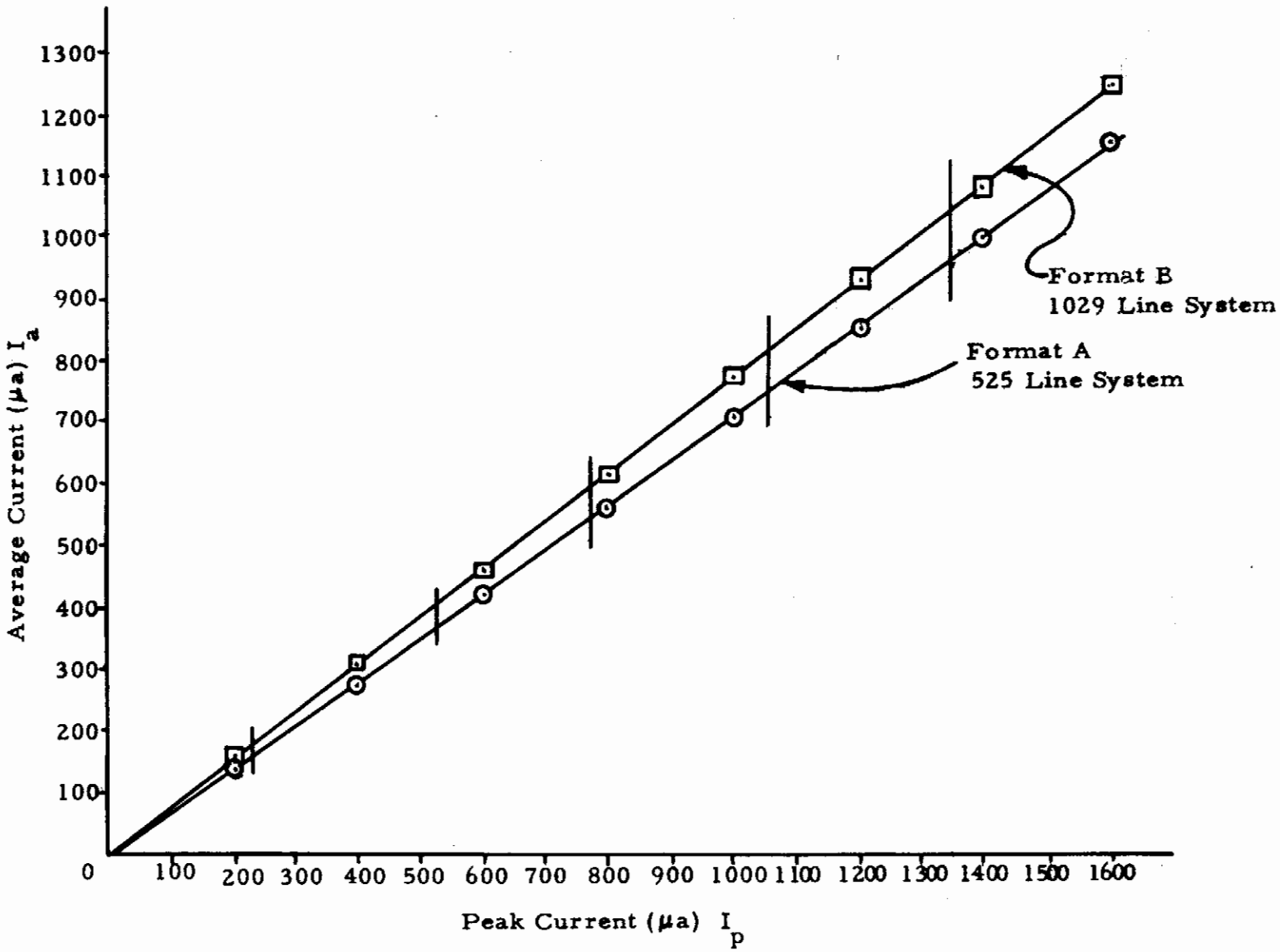


Figure 33 . Conversion Chart Peak to Average Current for Format A and Format B 7WP4 Evaluation

PHASE I

APPENDIX III

CATHODE-RAY TUBE BRIGHTNESS DATA

The analysis requires an indication of values for the cathode-ray tube phosphor output over small incremental areas. With this information, the brightness output of any format can be predicted for large areas.

Ordinary photometers average the total light energy received on their photocell surface, and ordinary optical systems can be employed to obtain the desired field of view. For the present analysis, a Spot Brightness meter was used. The optical system provided a narrow angle of coverage so that a very small area of light source was measured. The photometer was then arranged to view the cathode-ray tube face indirectly by looking through the projection lens, as explained in Section 5. The resulting field of view through the photometer eyepiece is shown in Figure 34. Note that this figure includes excited phosphor areas as well as the unenergized areas between scanning lines. Since the analysis requires the calculation of brightness output per unit length of scanning line, separation of the excited and unexcited phosphor areas was necessary.

Since the photometer field of view is known and the dimensions of this field can be calculated, the solution is obtained mathematically as follows:

It is known that the raster size was 5 in. (horizontal) by 3.75 in. (vertical) and that there were 482 active lines/frame (Appendix II) in the 525-line system. Line spacing is then obtained as follows:

$H = 5$ in.

$V = 3.75$ in.

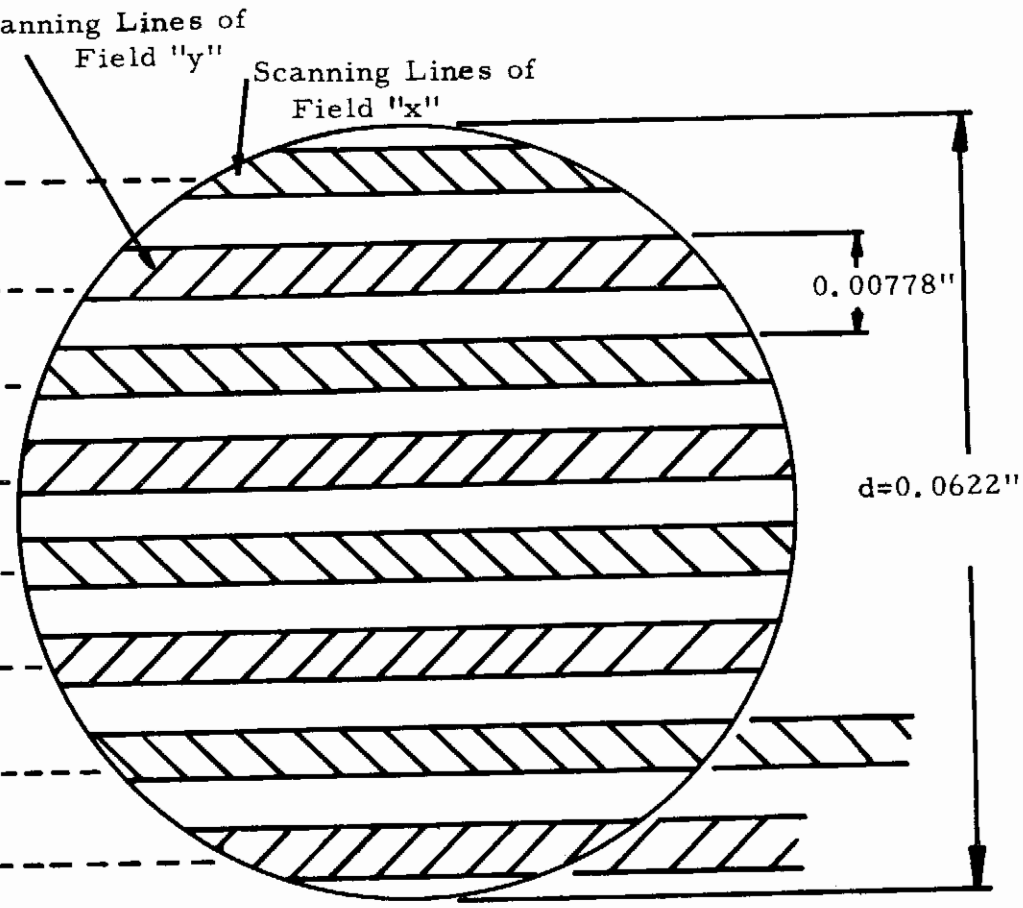
Aspect ratio $= 4 \times 3$

Each frame contains 482 active lines

$$\text{Line spacing} = \frac{3.75}{482} \text{ in.} = 0.00778 \text{ in.}$$

Aperture diameter = 8 line spacings $= 8 \cdot 0.00778 = 0.0622$ in dia.

Line	Field	Multiplier of Average Length
1	x	1.5
2	y	2.5
3	x	2.9
4	y	3.15
5	x	3.15
6	y	2.9
7	x	2.5
8	y	1.5



Aperture diameter = 3.188 units

Figure 34. Photometer Eyepiece Field of View under Low Current Setup Conditions

Figure 34 can then be dimensioned as shown.

The following values may now be obtained:

Actual Length of Scanning Lines for Fields x and y

1x = 0.0622 (1.5/3.188) = 0.029 in.
2y = 0.0622 (2.5/3.188) = 0.049 in.
3x = 0.0622 (2.9/3.188) = 0.057 in.
4y = 0.0622 (3.15/3.188) = 0.062 in.
5x = 0.0622 (3.15/3.188) = 0.062 in.
6y = 0.0622 (2.9/3.188) = 0.057 in.
7x = 0.0622 (2.5/3.188) = 0.049 in.
8y = 0.0622 (1.5/3.188) = 0.029 in.

Area relationships (a = area) are as follows:

a_1 = aperture area = $\pi d^2/4 = \frac{\pi}{4}(6.22^2) \cdot 10^{-4} = 30.4 \cdot 10^{-4}$ in.^{2}

a_2 = area scanned by field; x = total line length time line width.

Line width is equal to spot size. Selection of this size is difficult for it is not known where visual cutoff of the intensity profile occurs, and the level of ambient illumination is unknown, as explained in Section 5. The photometer merely averages the levels presented in the area shown in Figure 34.

Therefore the following assumptions are appropriate:

1. The emitting spot size, representing line width is 6 mils, which allows a distinct 2 mil separation between scanning lines.

2. The amount of emitted light in the 2 mil, unexcited area between lines is negligible, and will be considered as zero.

$\therefore\ a_2 = (0.029 + 0.057 + 0.062 + 0.049)(0.006) = (0.197)(0.006)$

$= 11.80 \cdot 10^{-4}$ in.^{2}

a_3 = area scanned by field y = $11.80 \cdot 10^{-4}$ in.^{2}

a_4 = area scanned by both fields = $(11.80 + 11.80) \cdot 10^{-4}$

$= 23.60 \cdot 10^{-4}$ in.^{2}

Once these values are known, the actual percentage of phosphor area in this aperture that emits light is known:

percent active area

(1) one field -- 11.80/30.4 = 39 percent
(2) two fields -- 23.6/30.4 = 78 percent

Spectral energy is emitted only in the active portion of the phosphor. Furthermore, an ideal scanning line is assumed as shown below in Figure 35. Diffusion and light spreading do occur, and the scanning electron beam has a finite width. This results in a seemingly Gaussian distribution of energy across the line width , as the photographs show. For the purpose of this discussion, it is felt that the idealized line is a satisfactory representation of actual cathode-ray tube output for analysis and comparison. It is also assumed that line width remains constant over the entire range of interest.

The photometer measures light in units of foot-lamberts, the average of the light energy presented across the detecting surface. A unit conversion must be performed to express this as light intensity per unit area, from which intensity can be deduced if area is known (see reference 4).

Then, given

F = light flux
I = light intensity
A = total area over which emitted light is measured

Then

$$F_2(\text{candelas/in.}^2) = F_1(\text{ft-lamberts}) \cdot 2.210 \cdot 10^{-3}$$

The various values of light flux (F_1) obtained from measurement of the 7WP4 are presented in Table 4.

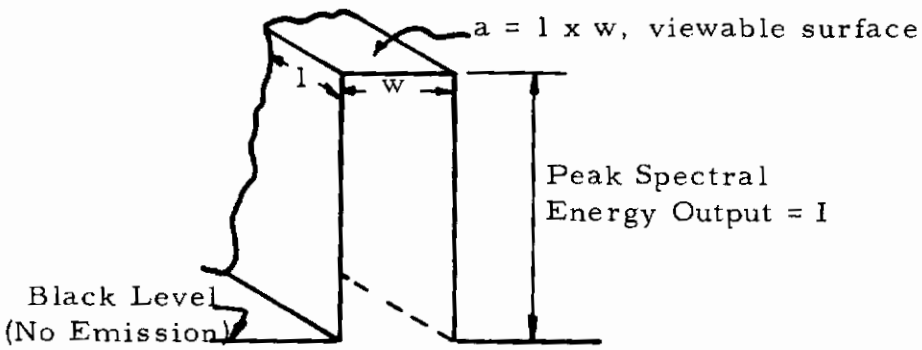


Figure 35. Idealized Scanning Line Intensity Profile

Table 4

7WP4 MEASURED BRIGHTNESS

a. 2 Fields/Frame for Normal 525-line System

Beam Current, μa		Measured Avg Brightness,* F_1, ft-lamberts	
Average*****	Peak	Old**	New**
50	69	10	--
75	104	15	--
100	139	20	40
150	208	30	--
200	278	40	90
250	344	46	--
300	417	50***	120****
400	555	65	150
500	695	78	180
600	835	90	210
645	895	100	--
700	970	110	250
800	1110	120****	260
900	1250	140	300
1000	1390	150	320

Table 4 (cont'd)

7WP4 MEASURED BRIGHTNESS

b. 1 Field/Frame for Special Condition, 525-line System

Beam Current, μa		Measured Avg Brightness,* F_1, ft-lamberts	
Average*****	Peak	Old**	New**
37	103	9	--
53	148	12.5	--
69	192	15	--
100	278	21	--
131	365	30	--
160	445	34	--
190	529	39	--
255	710	48	--
320	890	51	--
390	1080	68	--
430	1200	76	--
465	1290	80	--
535	1490	90	--
600	1670	110	--
645	1790	115	--

* Measured using a spectra spot brightness meter looking back through projection lens into cathode-ray tube face-plate. Vertical size 3-3/4 in. with 3 by 4 aspect ratio. Viewing angle of photometer covers 8 scanning lines, per Section 4.

** Old tube -- in operation approximately 200 hrs.; face visibly browned from x-ray bombardment. New tube -- taken from factory carton; no previous operational hours.

*** Change of scale on measuring instrument.

**** All values over 110 ft-lamberts are read on the upper end of a logarithmic meter scale and are not considered most accurate.

***** Average beam current measured with the following micro-ammeter: Systems Research Laboratories, Universal Polyranger, Model U, Serial No. 201816.

For the measured aperture shown in Figure 34,

$I = F \times a$

$$I_{avg} = \left[(2.21 \cdot 10^{-3}) F_1 \right] a_1 = (2.21 \cdot 10^{-3})(30.4 \cdot 10^{-4}) F_1$$

$$= 6.71 \cdot 10^{-6} F_1 \text{ candelas,}$$

where F_1 = measured value.

The level of flux emitted from only the activated area is

$$F = \frac{I_{avg}}{(a = \text{activated area})}$$

1. In the case of the one field per frame, 525-line system

$$F_{3A} = \frac{I_{avg}}{a_2} = \frac{6.71 \cdot 10^{-6} F_1}{11.80 \cdot 10^{-4}} = 0.570 \cdot 10^{-2} F_1$$

$$= 5.70 \cdot 10^{-3} F_1 \text{ candelas/in}^2$$

2. In the case of two fields per frame, 525-line system

$$F_{3B} = \frac{I_{avg}}{a_4} = \frac{6.71 \cdot 10^{-6} F_1}{23.60 \cdot 10^{-4}} = 2.84 \cdot 10^{-3} F_1 \text{ candelas/in.}^2$$

These data are presented in Table 5. They represent the light flux output from an excited area of 7WP4 phosphor as a function of peak beam current. The same data are plotted for both conditions of measurement in Figure 36, and an average is used for further analysis. The value of light flux/in. of scanning line, obtained by multiplying F_3 by the line width (one dimension of the area involved) is also shown ($F_3 \cdot 0.006$ in.).

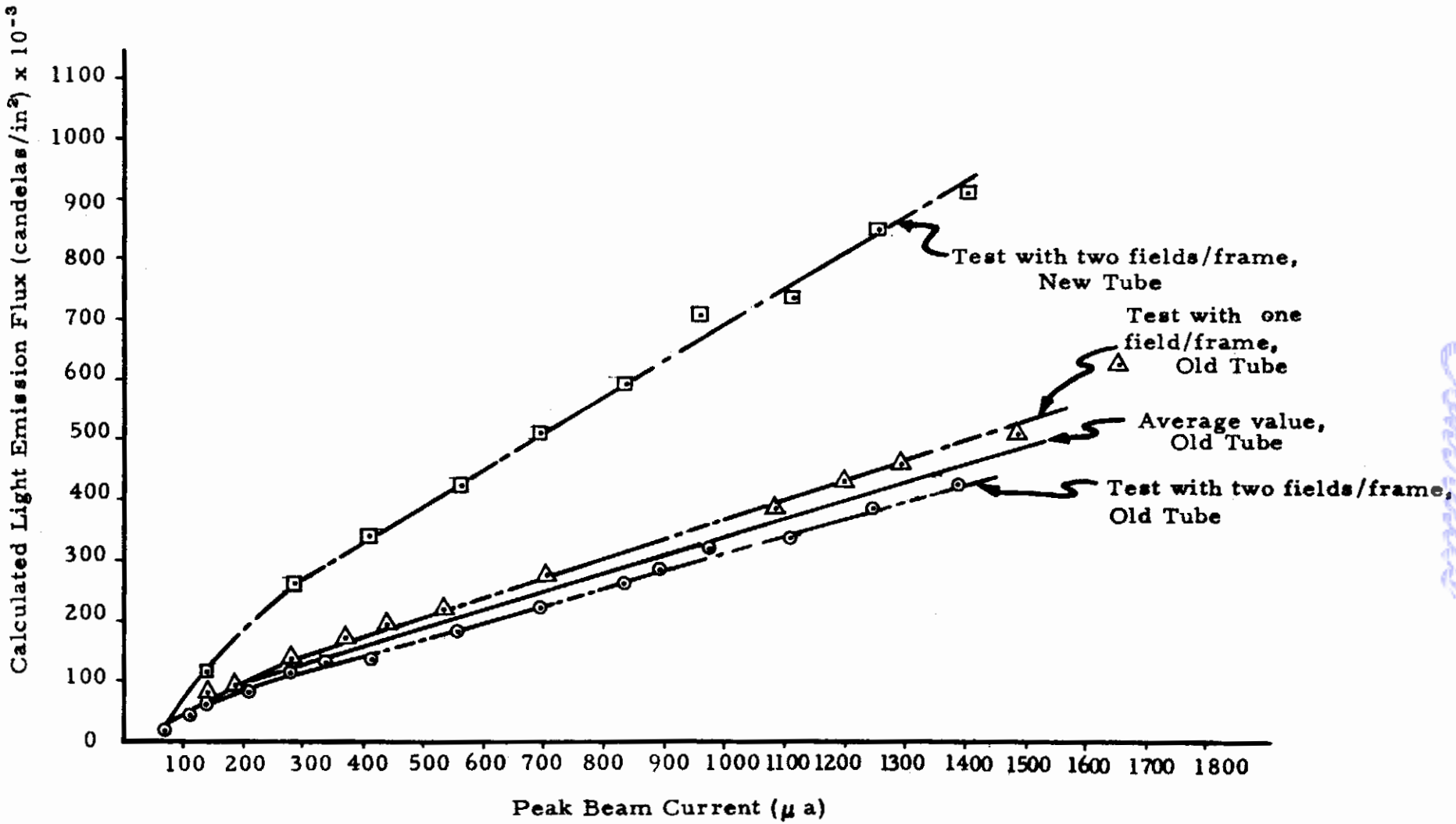


Figure 36. 7WP4 Phosphor Light Flux Output

Table 5

PHOSPHOR LIGHT FLUX OUTPUT

a. Two Field/Frame (see Figure 36)

Peak Beam Current μa	Calculated Emission Flux, F_{3B} candelas/in.$^2 \cdot 10^{-3}$	
	Old Tube ○	New Tube □
69	28	--
104	43	--
139	57	114
208	85	--
278	114	256
344	130	--
417	142	340
555	185	425
695	222	510
835	256	595
895	284	--
970	314	710
1110	342	738
1250	397	851
1390	426	910

b. One Field/Frame (Δ in Figure 36)

Peak Beam Current μa	Calculated Emission Flux, F_{3A} candelas/in.$^2 \cdot 10^{-3}$
	Old Tube
103	51.2
148	71
192	86
278	120
365	171
445	194
529	222
710	273
890	290
1080	388
1200	433
1290	456
1490	512
1670	630
1790	655

Table 5 (cont'd)

PHOSPHOR LIGHT FLUX OUTPUT

c. Values from Figure 36

Peak Beam Current μa	F_3, candelas/in.$^2 \cdot 10^{-3}$		$B_1 = F_3 \cdot w$* per inch of line times 10^{-6}	
	Old Tube	New Tube	Old Tube	New Tube
100	35	65	210	390
200	85	180	510	1080
300	125	260	750	1560
400	155	325	930	1950
500	180	385	1080	2310
600	215	450	1290	2600
700	250	510	1500	3060
800	275	570	1650	3420
900	310	625	1860	3750
1000	340	690	2040	4140
1100	365	750	2180	4500
1200	400	810	2400	4860
1300	425	875	2550	5250
1400	455	925	2730	5550

*B_1 = light emission per unit length of energized scanning line

Furthermore, it is known that phosphor light output is a direct function of the electron beam input to that specific area. The speed of scan (the rate at which this beam passes an area of phosphor) therefore influences brightness output. This must be considered if any other format of presentation is involved. A general expression for cathode-ray tube flux output has been developed in terms of a measured value in the same format:

$$F = \frac{I_1}{a} = \frac{F_1 \cdot a_1}{a}$$

To consider various formats, this must be referenced to scanning time as well as to area, as

$$F = \frac{I}{a} t$$

where

t = time required to scan the area in question.

Therefore

$$F_a = \frac{I_1 t_2}{a_2 t_1} = \frac{F_1 a_1 t_2}{a_2 t_1}$$

where

a_1 = activated phosphor area in original format

t_1 = incremental scan time in original format

F_1 = light flux output in original format

I_1 = phosphor emission intensity in original format

$$\left.\begin{array}{l} a_2 = \\ t_2 = \\ F_2 = \\ I_2 = \end{array}\right\} \text{equivalent parameters in new format}$$

The area of phosphor activated in each format of interest is obtained as follows:

$$a_T = w \cdot l \cdot n$$

where

w = scanning line width

l = scanning line length

n = number of active lines

The raster will occupy a total area of A, the product of raster height and width. Thus,

Format A:

525-line system
interlaced 2:1
raster 3.75 by 5 in.
field rate, 60 cps
$n = 482$ lines
$t_{line} = 63.4\ \mu sec/line$
horizontal blanking interval
$= 13.6\ \mu sec$
$t_{net} \approx 50\ \mu sec$
$t = \frac{50}{5} = 10\ \mu sec/in.$

Format B:

1029-line system
interlaced 2:1
raster 4 by 4 in.
field rate, 60 cps
$n = 942$ lines
$t_{line} = 32.4\ \mu sec/line$
horizontal blanking interval
$= 5\ \mu sec$
$t_{net} = 27.4\ \mu sec$
$t = \frac{27.4}{4} = 6.85\ \mu sec/in.$

(This indicates that for a particular given area of the activated phosphor, the brightness of Format B would be only 68.5 percent that of Format A due to the faster scanning.) We have assumed a line width "w" = 0.006 in. that remains constant over the brightness range of interest. However, a slight error will be introduced at higher beam current and brightness levels since it is known that width increases under those conditions. The result is that the calculated brightness values are slightly low for higher beam current levels.

Format A:

$a = w \cdot l \cdot n$
$= (0.006)(5)(482)$
$= 14.40\ in.^2$
$A = 3.75 \cdot 5 = 18.8\ in.^2$

Format B:

$a = w \cdot l \cdot n$
$= (0.006)(4)(942)$
$= 22.6\ in.^2$
$A = 4 \cdot 4 = 16\ in.^2$

At this point the following are known:

1. measured average brightness of the cathode-ray tube output
2. aperture area over which brightness was measured
3. percentage active area in the aperture
4. method of conversion to calculate light intensity over a specified phosphor area using (1), (2), and (3)
5. from (4) the light output in a unit length of scanning line for the format measured, as tabulated in Table 5.
6. the relationship between various formats, including consideration of scanning velocity
7. the area of activated phosphor and the raster area

(Note that a discrepancy is raised in the calculation of areas in Format B. The mathematical exercise yields a greater activated area of phosphor than the area contained within the raster dimensions, indicating that the scanning lines will overlap. Since the line width is greater than the line-to-line spacing, there will be no well-defined line structure in the raster at a 6-mil spot size. The only alternative is to assume the entire phosphor area is emitting, in which case the result (22.6 sq. in.) is arbitrarily reduced to 16 sq. in. Such results indicate that the tube is not suited for use in this format.)

It is now possible to use this information to calculate the brightness output that will be obtained for these formats.

The intensity output over the entire activated phosphor is calculated:

$$I = F_1 a_1 \frac{t}{t_1} = B_1 \cdot l \frac{t}{t_1} \cdot n \text{ candelas}$$

where

B_1 = flux output/ in. of scanning line in measured raster

n = number of lines (active)

Then

$$F_{avg} = \frac{I}{A} = \frac{B_1 \cdot l \cdot n}{A t_1} \text{ candelas/ in.}^2$$

The calculated results of this operation are presented in Table 6, which also presents the light output of only the scanned area for consideration of the effect of scanning speed. The following specific values were used to construct the table:

Format A:

$$I = B_1 l \frac{t}{t_1} n$$

$$= B_1 (5) \frac{10}{10} 482$$

$$= B_1 (2410) \text{ candelas}$$

$$F = \frac{I}{A} = B_1 \left(\frac{2410}{18.75} \right)$$

$$= B_1 (128) \text{ candelas/ in.}^2$$

$$= B_1 \left(\frac{128}{2.21} 10^3 \right)$$

$$= B_1 (57.9 \cdot 10^3) \text{ ft-lamberts}$$

Format B:

$$I = B_1 l \frac{t}{t_1} n$$

$$= B_1 (4) \left(\frac{6.85}{10} \right) (942)$$

$$= B_1 (2580) \text{ candelas}$$

$$F_{avg} = \frac{I}{A} = B_1 \left(\frac{2580}{16} \right)$$

$$= B_1 (161) \text{ candelas/in.}^2$$

$$= B_1 \left(\frac{161}{2.21} 10^3 \right)$$

$$= B_1 (72.8 \cdot 10^3) \text{ ft-lamberts}$$

These data are also presented in the graphs of Section 5.

Table 6

SUMMARY OF BRIGHTNESS VALUES FOR 7WP4

	Format A* 525-line System			Format B** 1029-Line System				
	Old Tube			Old Tube			New Tube	
Peak Beam Current μa	Avg Beam Current μa	Activated Area Output I, Candelas	Avg Raster Brightness, F_{avg}, Ft-lambert	Avg Beam Current μa	Activated Area Output I, candelas	Avg Raster Brightness, F_{avg}, ft-lambert	Activated Area Output I, candelas	Avg Raster Brightness, F_{avg}, ft-lambert
200	144	1.23	29.5	155	1.32	37	2.80	79
400	288	2.24	54	310	2.41	67.5	5.04	142
600	432	3.11	74.5	465	3.34	94	6.70	189
800	576	3.98	95	620	4.27	120	8.85	248
1000	720	4.92	118	775	5.28	148	10.70	301
1200	864	5.80	139	930	6.20	175	12.60	354
1400	1008	6.59	158	1080	7.08	192	14.38	404

* These data are a check of the analytical calculation. The results agree with the measurements shown in Table 4.

** These values are projections of predicted 7WP4 operation when the tube is used on a 1029-line format, 1000-line resolution system.

PHASE I

APPENDIX IV

SCANNING LINE STRUCTURE ANALYSIS

The object of this series of test runs was to evaluate the scanning line structure of a cathode-ray tube (specifically the 7WP4). The results are related to ultimate tube resolution, brightness, and contrast capabilities, as explained previously.

Equipment for the experiment was arranged as shown in Figure 37 to obtain a view of cathode-ray tube scanning lines projected through a suitable lens to a highly directive, high gain screen. The pattern was detected by a television camera with a long lens, arranged so that only a few of the projected lines were under analysis at any one time. A completely white field was projected at all times except when test chart patterns were used to insure proper optical focus in the test setup. The detecting camera was set at a 90-deg angle (on its side) so that the H scan of this device would be perpendicular to the H scan of the cathode-ray tube and would thus provide a cross-sectional view of the projected lines (intensity profile). The photographs shown in Figure 38 were obtained in this manner.

The video from the detector system was filtered through a low pass filter with the upper 3 db point at 1.25 mc to reduce the noise from vidicon detection. Higher frequency components are not used in the video representation of line structure. Tests made with a variable bandwidth amplifier verify that the bandwidth of 1.25 mc is not distorting the data but does remove noise.

The data obtained from the photographs were tabulated in Table 7 and were used to construct a scanning line intensity profile, as explained in Section 5 and as shown in Figure 39.

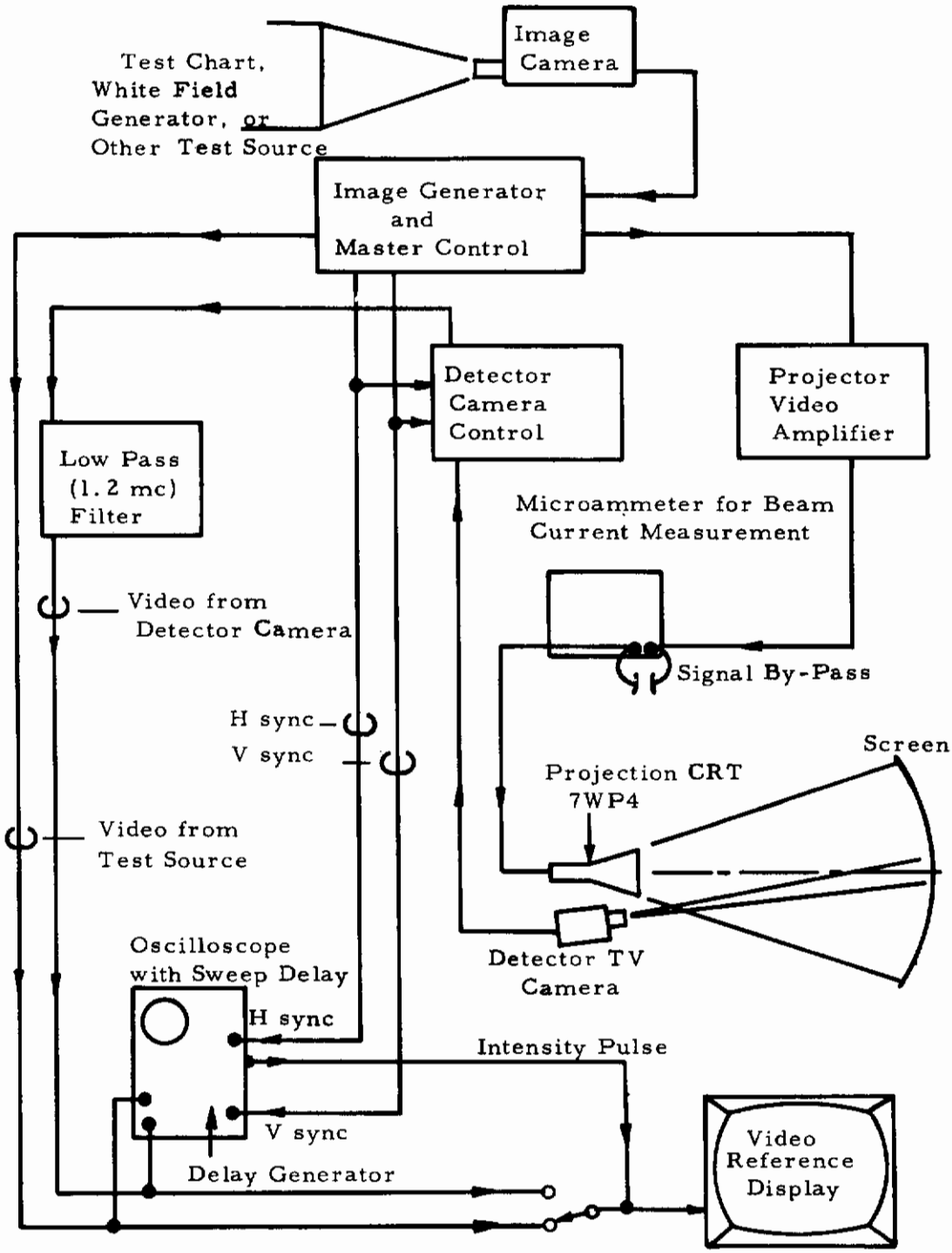


Figure 37. Test Set-up and Equipment Layout for Evaluation of 7WP4 Projection Cathode-Ray Tube

(a) Detail of horizontal line of detector camera scan as in (b) but magnified five times.

(b) One horizontal line of detector camera scan shown as surveying intensity profiles or projected lines. This line is located at the intensified point in (c) below.

(c) One field of detector camera as it accumulates information for 16.667 μ sec (262.5 horizontal lines). The spike indicates the particular horizontal line(s) being intensified and analyzed.

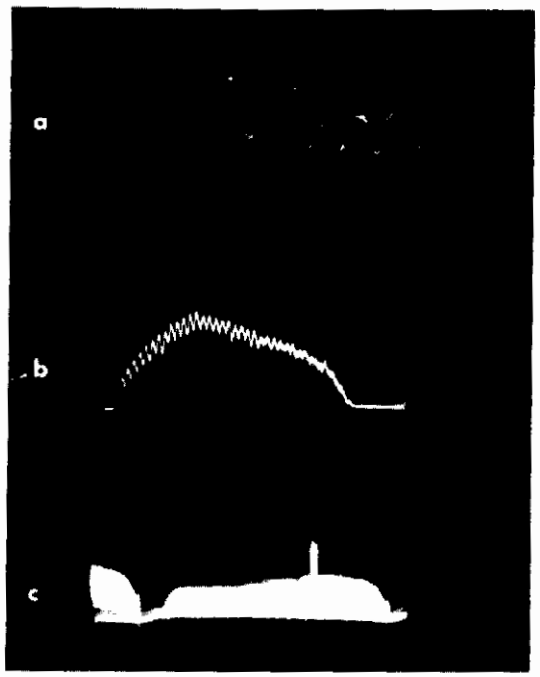


Figure 38. Typical Television Waveforms (Waveforms of video presented to projector unit and displayed on screen during evaluation. Note that flat white fields only are represented.)

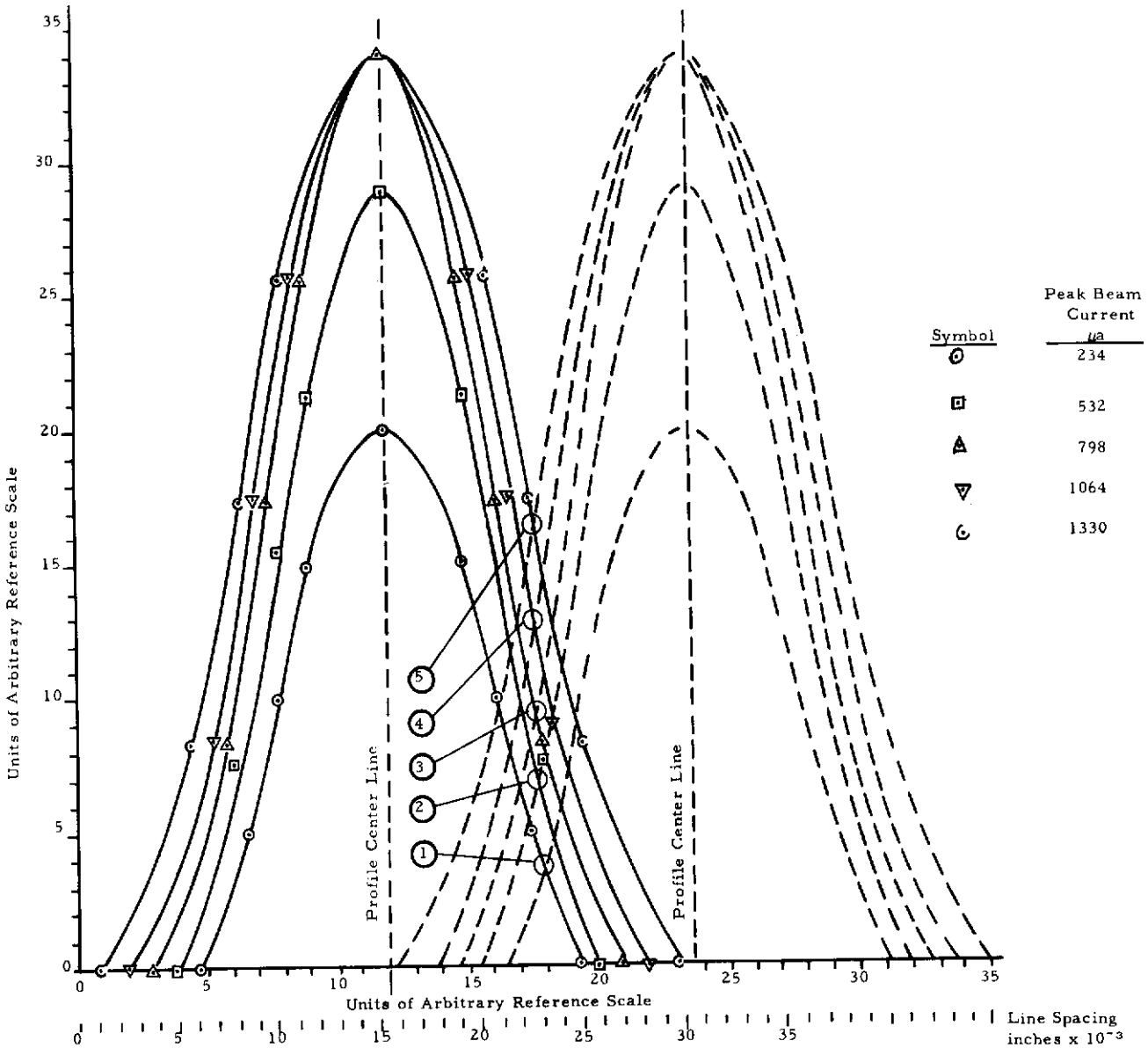


Figure 39. Scanning Line Intensity Profile Analysis

Table 7

Evaluation of 7WP4 Scanning Line structure at Expanded Vertical Deflection, Size, and Varying Beam Currents (one field per frame, 241 actual lines per field -- see Appendix III)

Photographic Information					Vertical Sweep Size			Peak Amplitude		Contrast	Line Density	Line Spacing		Line Width, in. (see figure 18)				
Figure No.	Scope Sensitivity v/cm	Scope Sweep Speed μsec/cm	Beam Current, μa Avg	Beam Current, μa Peak	Voltage, V, v	Current, I, ma	Raster Size, in. (see fig.)	Scaled, mm	Equiv. Voltage, v	%	line/in.	Scaled mm	Actual in.	100% (level)	75%	50%	25%	0 (baseline)
42(p)	0.01	H/50	88	234	7.0	734	6.94	40	0.04	100	34.8	22	0.0286	0	0.0078 (6 mm)	0.0104 (8 mm)	0.0143 (11mm)	0.0180 (14 mm)
40 (c)	0.02	↓	200	532	↓	↓	↓	29	0.058	↓	↓	↓	↓	↓	0.0078 (6 mm)	0.0104 (8 mm)	0.0163 (12 mm)	0.0195 (15mm)
40 (b)	0.02	↓	300	798	↓	↓	↓	34	0.068	↓	↓	↓	↓	↓	0.0078 (6 mm)	0.0118 (9 mm)	0.0169 (12mm)	0.0235 (18 mm)
40 (a)	0.02	↓	400	1064	↓	↓	↓	34	0.068	↓	↓	↓	↓	↓	0.0091 (7 mm)	0.0130 (10 mm)	0.0176 (12mm)	0.0260 (20 mm)
42 (b)	0	H/50	500	1130	7.0	734	6.94	34	0.068	100	34.8	22	0.0286	0	0.0104 (8 mm)	0.0143 (11 mm)	0.0195 (15 mm)	0.0286 (22 mm)

Note: Dimensions in parenthesis and/or noted in mm are scaled from photographs, Figures 40, 41, and 42.

The intensity profile was then used to calculate the obtainable contrast at a specified resolution and beam current as follows:

Vertical Resolution = number of acceptable resolution lines in a vertical raster dimension

Specified Horizontal Resolution = number of bits of information discernible in a horizontal dimension equal to raster vertical dimension

Actual Horizontal Resolving Capacity = number of bits of information discernible in horizontal raster dimension = specified horizontal resolution multiplied by aspect ratio

Vertical Line Spacing, Center to Center - vertical raster size divided by number of lines = $\frac{v}{n} = d$

Horizontal Information Bit Spacing, Center to Center = horizontal raster size divided by number of information bits = $\frac{h}{n_1} = d_1$

Spacing from Bright Peak to Bright Peak = 2 x line spacing = 2d or $2d_1$

SAMPLE CALCULATION, FORMAT A

Given:

525-line system
4 by 3 aspect ratio
3.75 in. raster height, v
5.00 in. raster width, h
241 active lines/field
482 active lines/frame, n

1. For 100-line resolution in the vertical dimension of 3.75 inches

$$d = \frac{v}{n} = \frac{3.75}{100} = 37.5 \cdot 10^{-3} \text{ in.}$$

$2d = 75 \cdot 10^{-3}$ in. spacing, bright peak to bright peak

2. For 600-line vertical resolution at 798 μa peak beam current

$$d = \frac{v}{n} = \frac{3.75}{600} = \frac{3750}{600} 10^{-3} = 6.25 \cdot 10^{-3} \text{in.}$$

$$2d = 2 \cdot 6.25 \cdot 10^{-3} = 12.5 \cdot 10^{-3} \text{in.}$$

From the intensity profile, the peak profile value = 34
The profiles overlap at a profile level of 14.8. This overlap signifies that energy is coming from two scanning lines. Therefore the overlap represents 14.8 arbitrary divisions (Figure 39) from the line just written plus an equal amount from the adjacent white bit of information. Therefore the true value at overlap becomes

$$x = 14.8 + 14.8 = 29.6$$

and

$$\% \text{ contrast} = \frac{\text{Peak} - \text{Overlap}}{\text{Peak}} = \frac{34 - 29.6}{34} = \frac{4.6}{34} = 13.5\%$$

This process continues until the overlap value exceeds the peak. At this point no contrast can exist since the overlap value, representing black or dark information, is brighter than the peaks, which represent the brightest information. From this point on, the contrast is 0 percent. Results are tabulated in Table 8.

Two further considerations are important in vertical resolution analysis. One of these is what effect results due to the interlace of scanning lines, the other is the apparent reduced resolution due to Kell factor.

Due to the 2:1 interlaced format of scanning in both the systems under analysis, adjacent lines are not written at the same time, but vary by 16,667 μsec. Therefore if adjacent white bits of information occur, tests show that the first one will be decayed to 25% original intensity when the second one is written. Therefore an intensity overlap of adjacent bits is minimized. This phenomenon does not enter into the analysis of vertical resolution, for the definition of resolution calls for adjacent white and black bits of information; in the 2:1 interlaced system it is coincident that this means every alternate, or No. 2 field is blanked to present the resolution pattern. The space between scanning lines, normally visible on a raster pattern, is an undesired but necessary effect, and does not enter in the resolution measurement.

Table 8

CALCULATION OF VERTICAL RESOLUTION FORMAT A

(calculation of % contrast from plots of scanning line cross section shown in Figure 23, Section 5)

Vertical Resolution, TV Lines		Double Line Spacing, mil	Percent Contrast at Peak Beam Currents, μa, of				
			234	532	798	1064	1330
Theoretical	Actual						
100	70	75	100	100	100	100	100
200	140	37.5	100	100	100	100	100
300	210	25	100	100	100	98	84
400	280	18.75	100	88	71	66	46
500	350	15	62	55	44	23	6
600	420	12.5	26	19	13	0	0
700	490	10.7	0	0	0	0	0
800	560	9.375	0	0	0	0	0

Table 9

SUMMARY OF HORIZONTAL RESOLUTION, FORMAT A

(data are plotted in Figure 22, Section 5)

Horizontal Resolution, TV Lines		Double Line Spacing, mil	Percent Contrast at Peak Beam Currents, μa, of				
Specified	Actual		234	532	798	1064	1330
100	133	75	100	100	100	100	100
200	266	37.5	100	100	100	100	100
300	400	25	100	100	100	98	84
400	532	18.75	100	88	71	66	46
500	655	15	62	55	44	23	6
600	800	12.5	26	19	13	0	0
700	930	10.7	0	0	0	0	0
800	1064	9.375	0	0	0	0	0

The vertical data is observed as a series of horizontal bars. Since the scanning lines are nearly horizontal, and there is a space or void between lines, the pattern is chopped by the scanning raster. The severity of the effect is dependent upon the pitch of scanning lines, and therefore will vary as scanning format varies. The degradation has been estimated to cause the visible value to be 0.7 times actual resolution through experimental observations. This number is called Kell factor (Reference 1).

The contrast values for specific values of horizontal resolution are obtained by the same method. The horizontal information is written sequentially; the overlap value is therefore doubled (equal contribution from each bit) for use in the contrast calculation for Format A. A sample calculation is shown below, and the results are tabulated in Table 9.

3. For 600-line horizontal resolution at 798 μa peak beam current,

h_1 = a horizontal distance equal to vertical raster size, v

$$d = \frac{h_1}{n} = \frac{3.75}{600} = \frac{3750}{600} \cdot 10^{-3} = 6.25 \cdot 10^{-3} \text{ in.}$$

$$2d = 2 \cdot 6.25 \cdot 10^{-3} = 12.50 \cdot 10^{-3} \text{ in.}$$

From the intensity profile we find that the peak value at 798 μa beam current is 34 units, and the profiles overlap at a level of 14.8.

$$x = 14.8 + 14.8 = 29.6$$

$$\text{and \% contrast} = \frac{\text{peak} - \text{overlap}}{\text{peak}} = \frac{34 - 29.6}{34} = \frac{4.6}{34} = 13.5\%$$

The actual horizontal data presentation is

actual resolution = specified resolution times aspect ratio

$$= 600 \cdot \frac{4}{3} = 800 \text{ lines}$$

SAMPLE CALCULATION, FORMAT B

The calculation for Format B was performed in the same manner. The results are shown in Tables 10 and 11.

Given:

1029-line system
1 x 1 aspect ratio
4 in. raster height, v
4 in. raster width, h
471 active lines/field
942 active lines/frame, n

For 500-line vertical resolution at 798 μa peak beam current, the contrast ratio is found as follows:

$$d = \frac{v}{n} = \frac{4.00}{500} = \frac{4000}{500} \cdot 10^{-3} = 8 \cdot 10^{-3} \text{ in.}$$

$$2d = 16 \cdot 10^{-3} \text{ inches spacing, bright peak to bright peak}$$

From the intensity profile, the peak profile value = 34 units. The profiles overlap at a level of 7.9, and this level is contributed by each white bit. Therefore the true level is $2 \cdot 7.9 = 15.8$

$$\% \text{ contrast} = \frac{34 - 15.8}{34} = \frac{18.2}{34} = 54\%$$

This process is continued for various line spacings until contrast becomes 0 due to an excess overlap level.

The horizontal resolution is calculated in the same manner, using h_1 rather than v,

$$d = \frac{h_1}{n}$$

Note that $h_1 = h$ for the 1 x 1 aspect ratio format, and specified and actual horizontal resolution values are the same.

Table 10

VERTICAL RESOLUTION, FORMAT B

(Calculations of % contrast, with residual phosphor energy considered)

Vertical Resolution, TV lines Theoretical	Double Line Spacing, mils	Percent Contrast at Peak Beam Currents, μa, of				
		234	532	798	1064	1330
400	20	100	96	85	76	50
500	16	74	64	54	36	18
600	13.35	40	33	25	1	0
700	11.2	10	3	0	0	0
800	10	0	0	0	0	0
900	8.9	0	0	0	0	0
1000	8.0	0	0	0	0	0
1100	7.25	0	0	0	0	0
1200	6.7	0	0	0	0	0

Table 11

HORIZONTAL RESOLUTION, FORMAT B

Horizontal Resolution, TV lines	Double Line Spacing, mils	Percent Contrast at Peak Beam Current, μa, of				
		234	532	798	1064	1330
400	20	100	96	85	76	50
500	16	74	64	54	36	18
600	13.35	40	33	25	1	0
700	11.2	10	3	0	0	0
800	10	0	0	0	0	0

EXPERIMENTAL VERIFICATION, RUNS II AND III

Two experimental runs were performed using the 525-line system to verify the analysis of resolution. The vertical deflection size was varied to adjust scanning line spacing and therefore the bit density of information. The photographs of data were tabulated (Tables 12 and 13) and were used to derive an intensity profile (see Figure 39) from which the following analysis was made:

Sample Calculation

1. From Figure 41:

   vertical size recorded at 6.94 in.
   241 active lines/field, one field/frame
   line density = 241/6.94 = 34.8 lines/in.
   peak-to-peak spacing = 1/line density = $\frac{1}{34.8}$ = 0.0286 in.
   line (bit) spacing = 0.0143

In a 3.75-in. horizontal dimension, the number of lines is 3.75/0.0143 = 262 lines and the percent contrast is the peak intensity reading at the selected raster size divided by the peak level at 6.94 in. vertical size.

These calculations were made at varying equivalent resolution values for both 234-and 798-μa beam currents, as shown in Tables 12 and 13 for Runs I and II. The data obtained from these tests are plotted in Figure 22 (Section 5) for comparison with the calculated values.

	a	b	c	d	e	f
Vertical Deflection (inches)	6.94	6.94	6.94	6.4	5.2	4.4
Average Beam Current (μ a)	400	300	200	300	300	300
Peak Beam Current (μ a)	1064	798	532	798	798	798

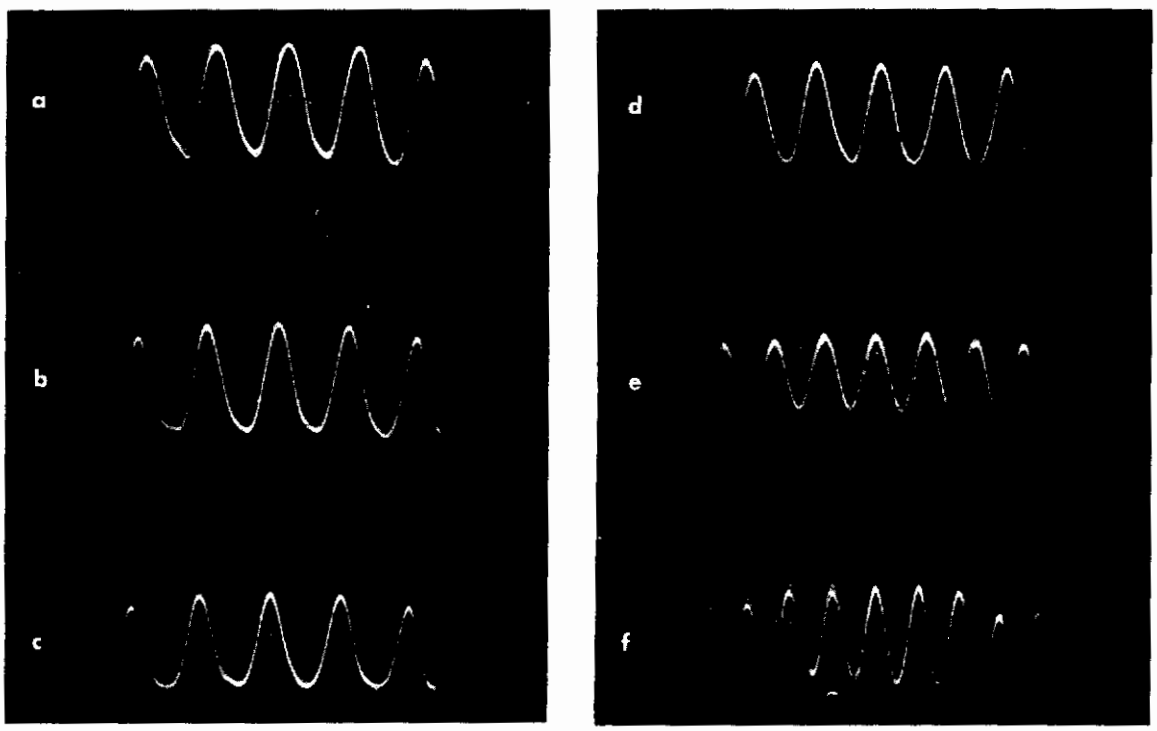


Figure 40. Detected Waveforms (The presentation of scanning line structure under analysis. Data is shown for varying beam current or varying vertical deflection size for the 7WP4 projection kinescope.)

	g	h	i	j	k	l
Vertical Deflection (inches)	3.8	3.2	3.2	3.8	4.4	5.2
Average Beam Current (μ a)	300	300	88	88	88	88
Peak Beam Current (μ a)	798	798	234	234	234	234

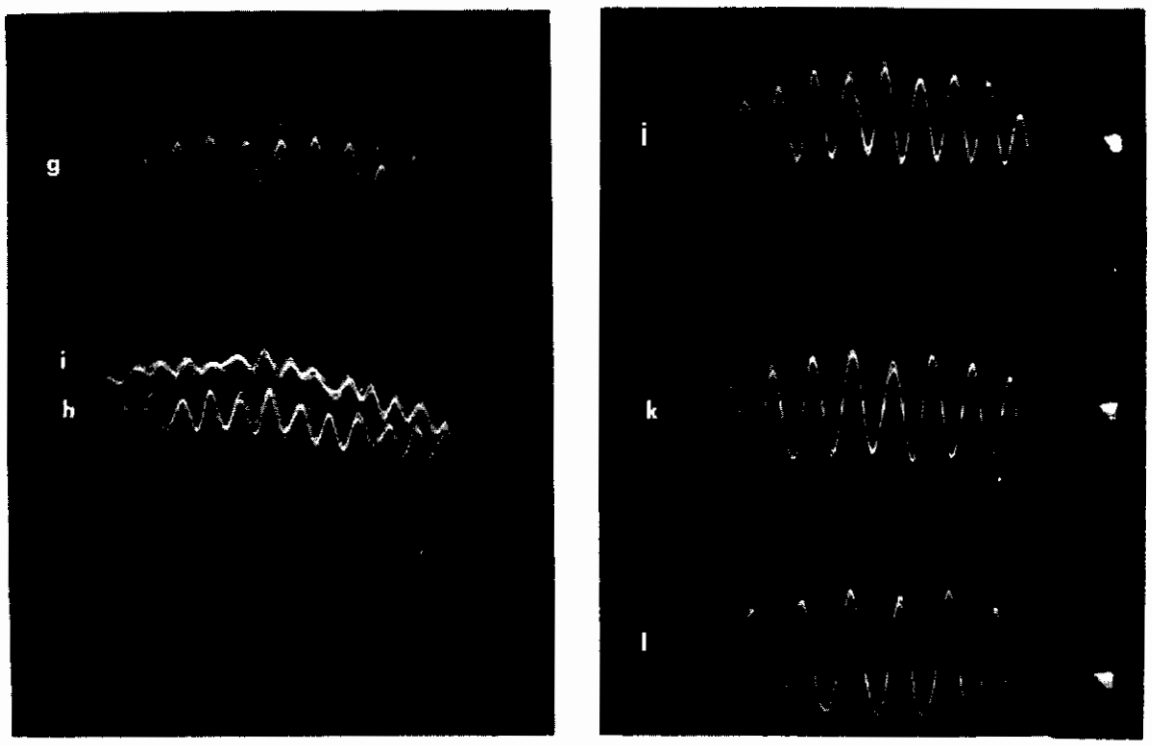


Figure 41. Detected Waveforms (The presentation of scanning line structure under analysis. Data is shown for varying beam current or varying vertical deflection size for the 7WP4 projection kinescope.)

	m	n	o	p	q
Vertical Deflection (inches)	6.4	6.94	6.94	6.94	6.94
Average Beam Current (μa)	88	142	500	88	500
Peak Beam Current (μa)	234	376	1330	234	1330

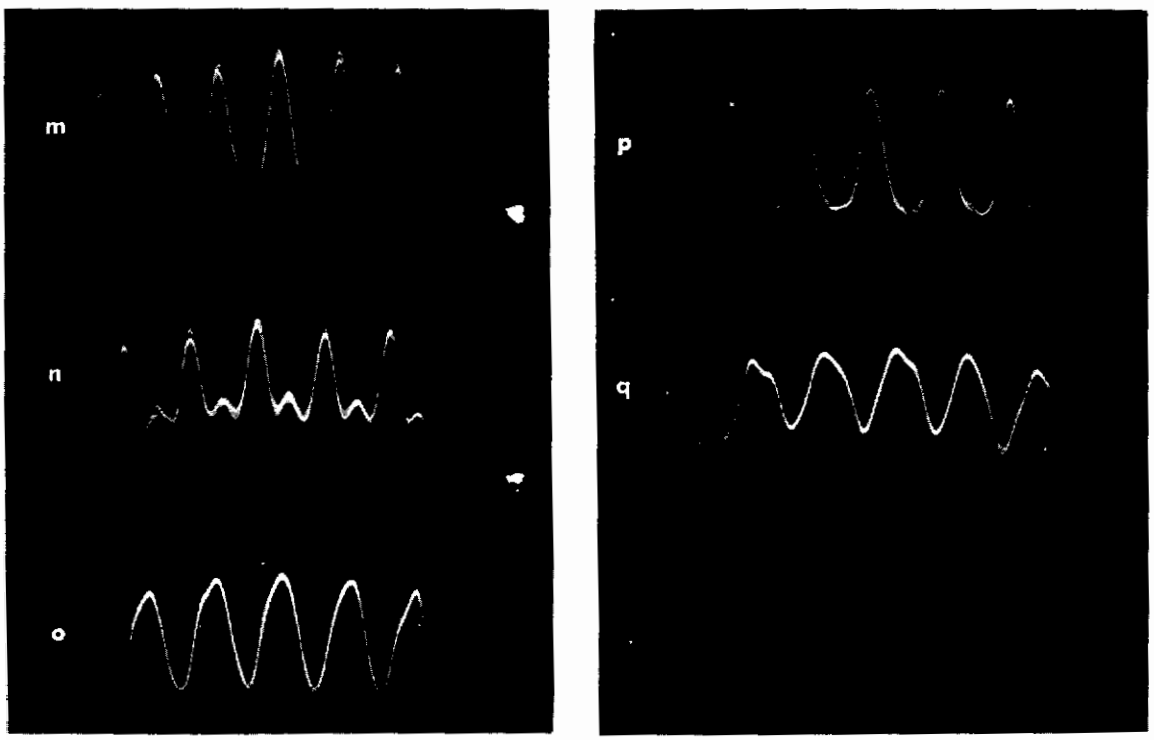


Figure 42. Detected Waveforms (The presentation of scanning line structure under analysis. Data is shown for varying beam current or varying vertical deflection size for the 7WP4 projection kinescope.)

Table 12

Evaluation of Contrast Obtainable with High Beam Current as Vertical Size Varies (one field per frame, 241 active lines per field) Run II

Photographic Information			Beam Current, μa		Vertical Sweep Size			Peak Amplitude		Contrast	Line Density	Line Spacing		Equivalent Horizontal Resolution 5" Raster
Figure No.	Scope Sensitivity v/cm	Scope Sweep Speed μsec/cm	Avg	Peak	Voltage, V, v	Current, I, ma	Raster Size, in.	Scaled, mm	Equiv. Voltage v	%	line/in.	Scaled mm	Actual in.	
40 (b)	0.02	H/50	300	798	7.0	734	6.94	34	0.068	100	34.8	22	0.0286	262
40 (d)	0.02	↓	↓	↓	6.4	671	6.35	30	0.060	88	38	20	0.0264	285
40 (e)	0.02	↓	↓	↓	5.2	545	5.10	23	0.046	68	47	17	0.0213	352
40 (f)	0.01	↓	↓	↓	4.4	461	4.30	29	0.029	43	56	14	0.0178	421
41 (g)	0.01	↓	↓	↓	3.8	398	3.70	13	0.013	19	65	11.5	0.0154	487
41 (h)	0.01	H/50	300	798	3.2	335	3.10	7	0.007	10	78	9	0.0128	588

Table 13

Evaluation of Contrast Obtainable with Lower Beam Current as Vertical Size Varies (one field per frame, 241 active lines per field) Run III

Photographic Information			Beam Current, μa		Vertical Sweep Size			Peak Amplitude		Contrast	Line Density	Line Spacing		Equivalent Horizontal Resolution 5" Raster
Figure No.	Scope Sensitivity v/cm	Scope Sweep Speed μsec/cm	Avg	Peak	Voltage, V, v	Current, I, ma	Raster Size, in.	Scaled, mm	Equiv. Voltage v	%	line/in.	Scaled mm	Actual in.	
42 (p)	0.01	H/50	88	234	7.0	734	6.94	41	0.041	100	34.8	22	0.0286	262
42 (m)	↓	↓	↓	↓	6.4	671	6.35	41	0.041	100	38	20	0.0264	285
41 (l)	↓	↓	↓	↓	5.2	545	5.10	38	0.038	93	47	17	0.0213	352
41 (k)	↓	↓	↓	↓	4.4	461	4.30	30	0.030	73	56	14	0.0178	421
41 (j)	↓	↓	↓	↓	3.8	398	3.70	26	0.026	64	65	11.5	0.0154	487
41 (i)	0.01	H/50	88	234	3.2	335	3.10	13	0.013	32	78	9.5	0.0128	588

PHASE I

APPENDIX V

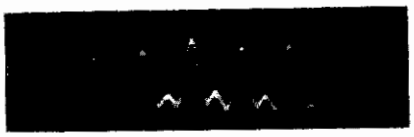
MISCELLANEOUS DATA

A series of tests was undertaken in Run IV which illustrate the relationship existing in the display of one field per frame as opposed to two fields per frame presented for nominal current levels in Figure 43.

Figure 44 shows a similar comparison for higher levels of beam current. In addition a superimposed set of waveforms (Figure 45) is shown for alternate fields, demonstrating a profile similar to the one constructed in Appendix IV (Figure 42, which shows waveforms for a range of beam current and deflection size conditions, as noted).

The final photograph is verifying the effectiveness of blanking out alternate fields. The information obtained from Figure 46 shows sufficiently good suppression to justify the assumption that no measurable, (therefore, significant) beam current flows during the suppressed interval.

The numerical data from test photographs is presented in Table 14 for those that are not described in Tables 7, 12, or 13.

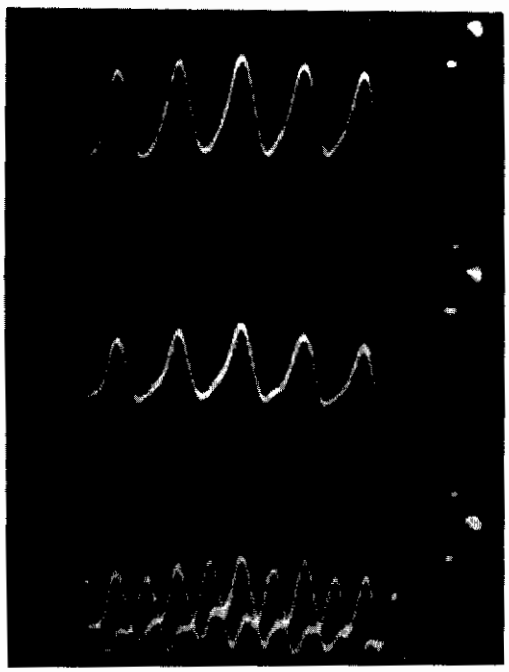


(a) Two fields per frame are displayed. Vertical deflection size = 6.94 inches: average current level is set at 88 μa with one field per frame and rises to 142 μa when two fields per frame are displayed. Residual scanned energy from alternate unblanked field is evident between profiles.

(b) One field per frame is displayed.
Vertical Deflection Size 6.94 inches
Average Beam Current 88 μa
Peak Beam Current 234 μa
Unwanted residual energy is eliminated by blanking alternate fields. The current does not show a 2:1 ratio as result of change from two to one fields, as was anticipated, because there is not a 100-percent active time of scan in each field. This small percentage of "blanked" time lowers the ratio.

Figure 43. Comparison of One and Two Fields/Frame

Vertical Deflection Size 6.94 inches
in all cases

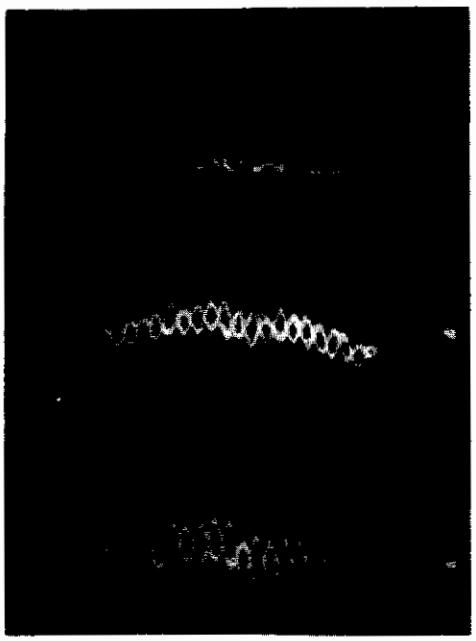


(a) One field/frame,
I = 500 μa (set)

(b) Two fields/frame;
I rose to 700 μa and
residual energy from
alternate field is
evident in waveform

(c) Two fields/frame,
I remaining at 700 μa .
Scope adjusted for display
of superimposed scan
lines from alternate
fields.

Figure 44. Comparison of One and Two Fields/Frame



(a) Vertical Deflection Size is 6.95 inches. System setup at I = 88 μa at one field/frame, then two fields/frame are displayed while superimposed.

(b) Vertical size reduced to half previous value (3.38 in.). Current is the same as in (a). Note reduction in obtainable contrast between bright peaks.

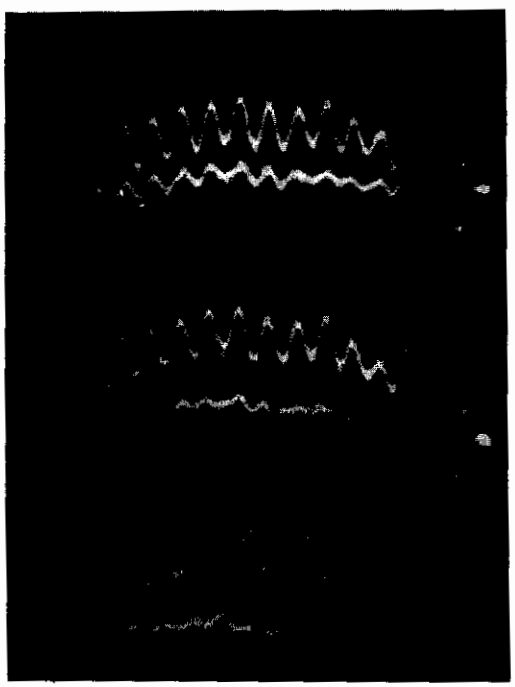
(c) Vertical size remains at 3.38 inches; current raised to maximum obtainable of 750 μa (avg). Note that even though peak brightness rises, contrast is not improved by a corresponding ratio and resolution suffers.

Figure 45. Survey of Contrast Ratio Waveforms at Various Beam Current Levels

Setup Conditions:

System set at 3.38-in. vertical deflection size and oscilloscope presentation arranged to display residual beam current and phosphor excitation present in the blanked alternate field (lower Line). In each instance the top trace shows the scanning line profile, the lower trace shows residual phosphor output (scanning line profile) during the suppressed field, demonstrating the effectivity of field suppression.

Suppression appears sufficiently good to justify assumption that no measurable beam current flows in this interval



(a) Average beam current 100 μa

(b) Average beam current 200 μa

(c) Average beam current 300 μa

Figure 46. Study of Actual Current Flow during Suppressed Field

Table 14

RUN IV, TABULATION OF PHOTOGRAPHIC DATA

Figure No.	Photographic Information		Beam Current, μa		Vertical Sweep Size,
	Scope Sensitivity,	Scope Sweep Speed	Avg	Peak	In.
	v/cm	μsec/cm			
13 (d)	0.2	2000	88	234	3.38
(e)	0.1	H/10	88	234	3.38
(f)	0.01	H/50	88	234	3.38
13(a)	0.1	2000			
(b)	0.1	100	—	—	—
(c)	0.1	10	—	—	—
42 (a)	0.01	H/50	142	190	6.95
(b)	0.01	H/50	88	234	6.95
43 (a)	0.02	H/50	500	1330	6.95
(b)	0.02	H/50	700	935	6.95
(c)	0.02	H/50	700	935	6.95
44 (a)	0.01	H/50	142	190	6.95
(b)	0.01	H/50	142	190	3.38
(c)	0.01	H/50	750	1000	3.38
45 (a)	0.01	H/50	100	266	3.38
(b)	0.01	H/50	200	532	3.38
(c)	0.01	H/50	300	798	3.38

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13. ABSTRACT In Phase I of this report, a study of large area image display by projection television was undertaken to evolve techniques of suitable image generation for astronautical flight simulation training. It was necessary to develop a technique to evaluate projected images. The display provided by the research apparatus, the close-circuit television system from an F-151 Fixed Gunnery Trainer, was evaluated and performance characteristics of the 7WP4 performance in an ultra-high resolution television system revealed the tube to be unsuited to high resolution service. In Phase II of this report, the projector in the F-151 television system is converted from a conventional 525-line system to a high resolution 1029-line system. The 525-line format operated at 30 frames per second, with a horizontal scanning frequency of 15.75 kc and a vertical scanning frequency of 60 cps. In the 1029-line system, the frame rate and vertical scanning frequency were retained, but the horizontal scanning frequency was changed to 30.87 kc. The vertical sweep generator, sweep protection, and projection control circuits were duplicated; a video amplifier and horizontal sweep generator were developed; and volume of the control equipment was reduced from 144 to 32 cubic feet. Performance of the 7WP4 tube exceeded the prediction: limiting horizontal resolution is 650 to 700 lines with a well defined vertical raster. Research indicates that a study into basic CRT characteristics is in order, particularly for use in display devices.

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