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incorporated

CRT PROJECTION OPTICS

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SOCIETY FOR INFORMATION DISPLAY
SID

Seminar presented to the Society for Information Display (SID)
in Anaheim, California, May 6, 1991.

SEMINAR M-7

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Summary

The objective of this seminar is to provide a general background and a basic understanding of some of the tradeoffs involved in the specification, design and incorporation of projection optics in CRT projection systems. Broadcast standards, the visual requirements of the image and the effect of CRT and screen characteristics are considered. Overall system requirements specific to rear- and front-screen three-lens systems are emphasized. The evolution of the projection lens itself is covered in detail. Manufacturability and cost considerations are included throughout as appropriate.

ISSN0887-915X/91/0000-M-7-$1.00 + .00

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Introduction

The Types of CRT Proiection Svstem

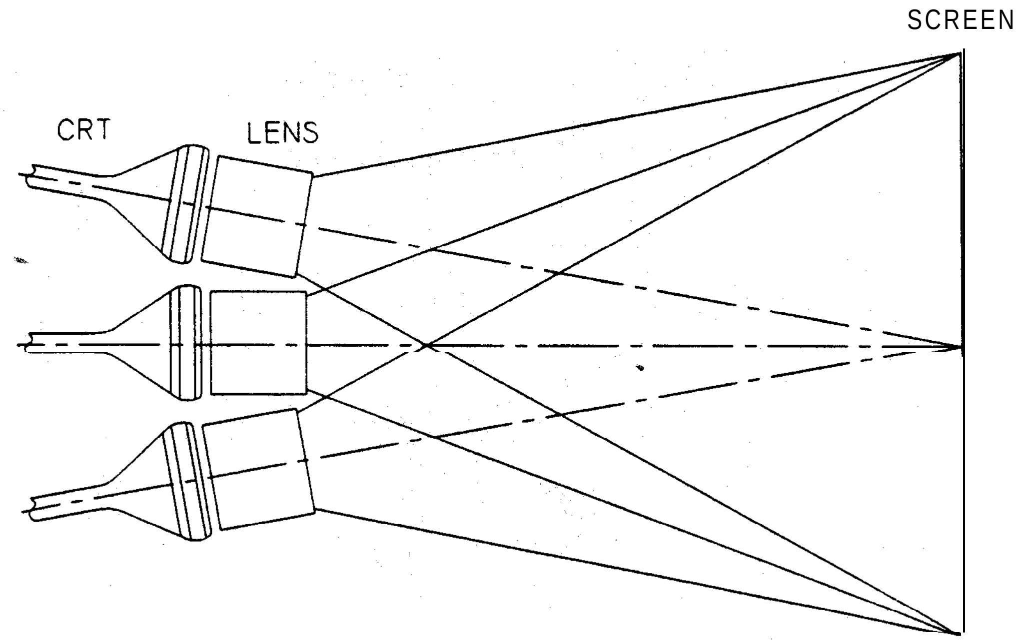
There are two basic design types for CRT projection systems, the three lens configuration and the one lens configuration (see Figure 1). In the three-lens system, the final color image results from the superposition of the images from three monochromatic CRT's. In the one-lens system, a combination of dichroic mirrors is used to effectively superimpose the three CRT phosphors, and a single lens is then used to project this "color" phosphor onto the viewing screen.

Although some aspects of system design are common to both of these configurations, the differences are significant. This presentation will deal exclusively with the three-lens configuration, since it is by far the most common design in both consumer and industrial projection systems available today. It should be noted, however, that the one-lens system configuration will probably be preferred for LCD projection systems in the future, and will take on a growing importance as these systems are introduced.

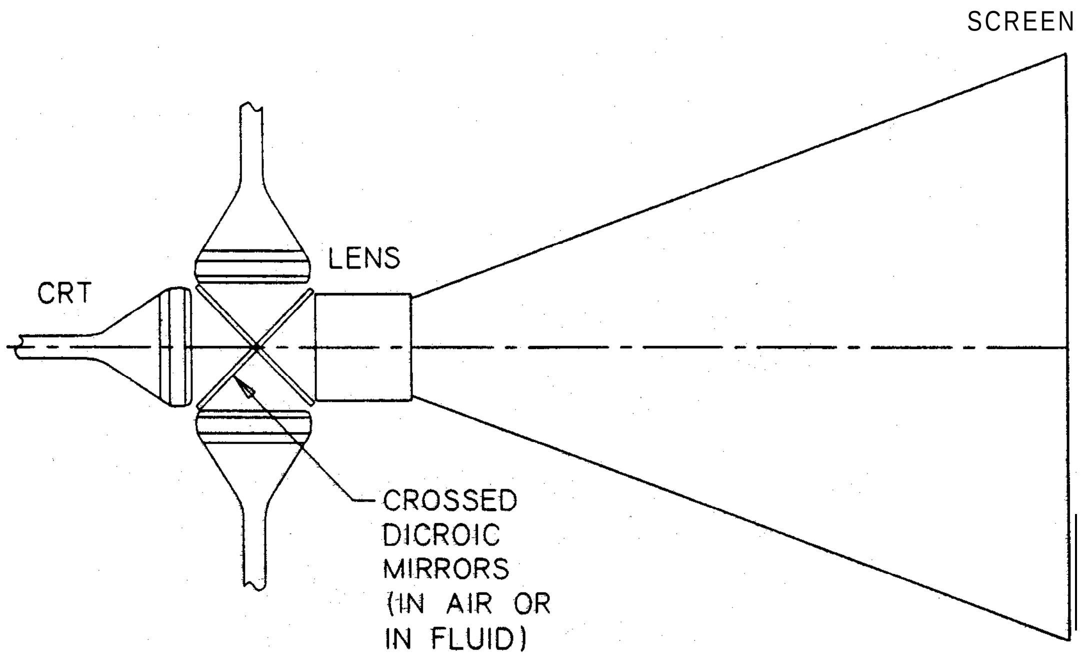
The three-lens configuration is used in both front screen and rear screen applications, and the basic optical components of both are the same (see Figure 2). A CRT produces an image on the phosphor surface, and a projection lens is used to form a real image of the phosphor on the surface of a screen, which directs the light to the viewer. Each of these three components, the CRT, the screen and the projection lens, will be discussed in what follows. The special design considerations for rear screen versus front screen systems will also be addressed. Since system cost has been and will continue to be a driving factor in the design of CRT projection systems, cost considerations will be considered throughout the presentation where appropriate.

Broadcast Standards for Proiection Systems

Broadcast standards are an important consideration in the design of CRT projection systems because they, along with the minimum CRT spot size, determine the resolution requirements for the projection lens. It is not within the scope of this presentation to deal with the pros and cons of the different standards which have been suggested for HDTV or the many "step-up" systems. It is sufficient for our purposes to state that the number of lines per scan, the scan rate, the phosphor size and the broadcast bandwidth for a particular standard will determine the smallest resolution element on the phosphor. It will be assumed that the CRT spot size is sufficiently small to allow detail of the size of this resolution element to be resolved; otherwise, the CRT spot size itself will set the smallest CRT resolution element size.



a. Three lens configuration



b . One lens configuration

Figure 1 Three lens and one -lens CRT projection configurations.

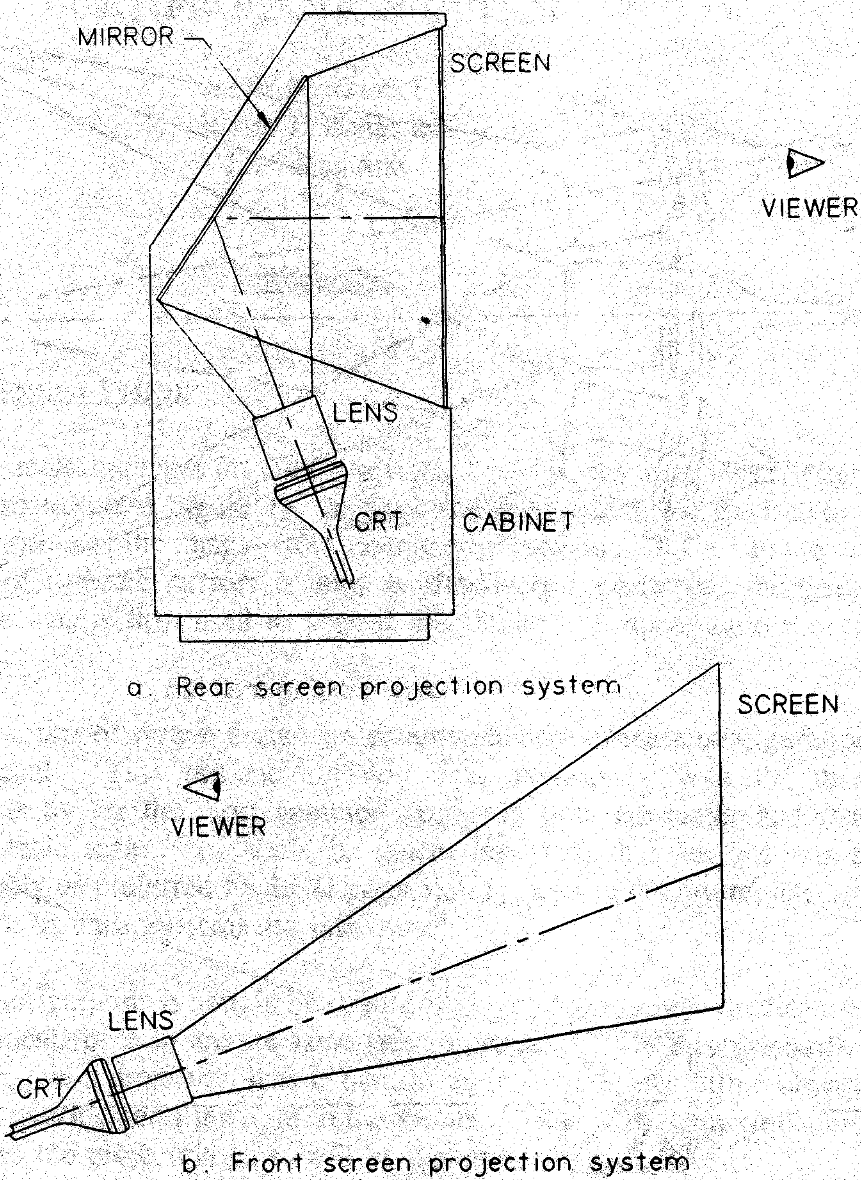


Figure 2 Rear and front screen projection systems

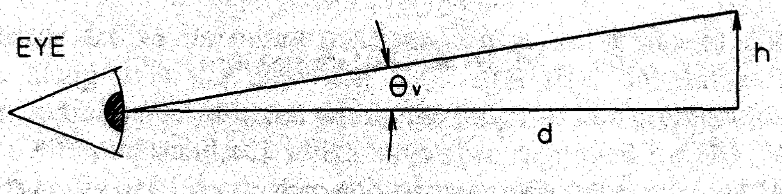


Figure 3 Visual angle θv of an object of height h at a distance d from the eye

Table 1 lists several broadcast standards, along with the important parameters of each. Also given in the table is the lens resolution required for each standard.

Table 1: TV Systems: Relative Comparison

	Horizontal Resolution	Horizontal Rate (KHz	Vertical Resolution	Aspect Ratio	Lens Resolution lp/mm
Advanced TV					
HDTV	1,920	34	1080i	16:9	6
	1,280	45	720p	16:9	6
SDTV (Standard Digital)					
	640-704	31	480p	4:3	5
NTSC	768	16	483	4:3	2
Current Standard					
NTSC	768	16	483	4:3	2
Current Institutional					
- Video	1,000+		N/A	4:3	5
- Data	1,600+		N/A	4:3	10
- Graphics	2,000+		N/A	4:3	12

*RGB Bandwidth
+Input dependent, equivalent to optical resolution

Visual Acuity and Optimum Viewing Distance

Once the required lens resolution has been determined from the system broadcast standard or CRT spot size, it is possible to compute an "optimal" viewing distance for a particular screen size. This can be accomplished by using the visual acuity of the eye, which is the final sensor in the projection systems of interest here.

The visual angle Θ_v can be defined as the angle subtended by an object of height h at a distance d from the eye (see Figure 3). It can be seen that

$$\Theta_v = \tan^{-1} (h/d).$$

The visual acuity is defined as the smallest visual angle that can be resolved by the eye. "Normal" visual acuity is commonly assigned a value of one minute of arc. If the equation above is rearranged

$$d = h / \tan \Theta_v \qquad (1)$$

and Θ_v is given a value of one minute, the resultant expression can be used to find the distance from the eye at which an object of height h can be placed and just be resolved by the eye.

Optimal viewing distance is determined in the following way. It is first necessary to determine the magnification of the system, which is simply the desired screen size divided by the size of the active phosphor area,

magnification (m) = screen size / phosphor size.

The resolution unit on the screen will be the product of the system magnification and the resolution unit on the CRT, which has been determined by the broadcast standard and CRT spot size,

$$h_s = m\, h_{CRT}.$$

If h_s is now substituted for h in equation 1 with Θ_v equal to one minute of arc, the resultant d is the optimal viewing distance d_{opt},

$$d_{opt} = h_s / \tan(1') = 3438\, h_s.$$

This distance is called the optimal viewing distance for the following reason. At distances larger than d_{opt}, the normal viewer cannot resolve the finest detail present on the screen. At distances smaller than d_{opt}, the viewer may observe a lack of resolution in the detail of the image, because no detail smaller than h_{CRT} can be resolved on the phosphor.

Note that in the above derivation, a particular screen size was assumed and an optimal viewing distance was determined using that screen size (see equation 1). Obviously, it is also possible to assume a particular optimal viewing distance, and then to compute the required screen size for this viewing distance. In fact, optimal viewing distance is most often used in this manner in system design.

Although the computation involving optimal viewing distance is a useful guide for system design, in general it can be considered no more than a guide. In certain applications, such as simulators, it is possible to very precisely define the position of the viewer; in these cases optimal viewing distance can be used rigorously as a system design parameter. However, in most consumer and industrial applications it is only possible to define viewer position in general terms, so in these cases the optimal-viewing distance is of a more limited value.

The CRT

In any optical system, the quality of the image can be no better than the quality of the object. In the case of conventional projection TV, the CRT source dictates the starting point from which the optical system begins its critical function.

Construction

The CRT construction has remained basically unchanged for many years. The CRT consists of four major components (see Figure 4). The bulb is the glass envelope which maintains the high vacuum required for 'the electron beam as well as the super-structure to hold the other components in alignment. The electron gun produces the electron beam which can be current modulated. The "focusing" of the beam employs either electrostatic or magnetic systems. The deflection section of the CRT controls where on the phosphor screen the beam will strike. This is typically done by a magnetic yoke or coil, but can also utilize electrostatic deflection. The screen, coated with a thin layer of phosphor on the inside surface, transforms the electron beam traces into luminescent lines which can be observed optically. A thin electrically conductive coating of aluminum or "dag" provides the anode potential at the phosphor screen.

The electron beam focusing technique is particularly important in that it dictates the resolution performance of the CRT. Magnetic focusing provides the highest resolution. Of the electrostatic designs, the high-voltage bipotential-focus gun is 30-50% higher resolution than is the low-voltage unipotential-focus gun.

By choosing the type of deflection and focus technique, a matrix of performance can be constructed (see Table 2).

Table 2 Vertical Resolution as a Function of Deflection Type and Focus Technique

Focus-Deflection CRT Configurations		
Focus	**Deflection**	**Resolution**
Electro-static	Electro-static	Moderate
Electro-static	Magnetic	Moderate-High
Magnetic	Magnetic	High

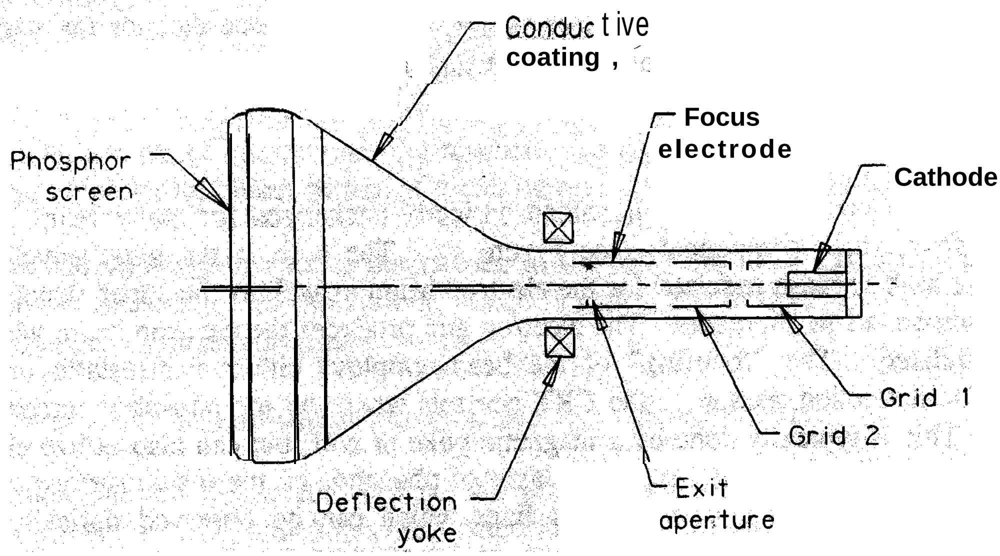


Figure 4 The cathode ray tube (CRT)

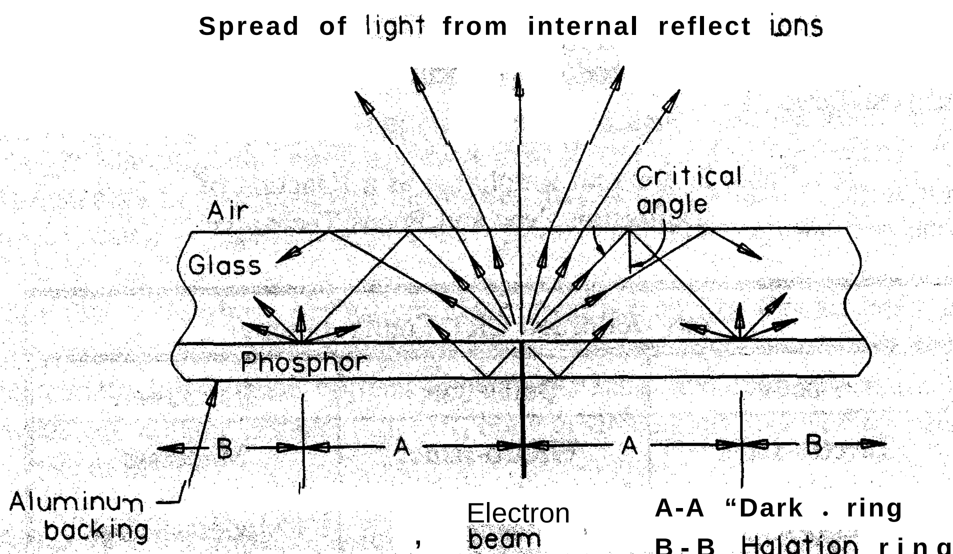


Figure 5 Halation in a CRT

Contrast

After resolution, contrast is perhaps the most important CRT performance attribute. Contrast can be described in terms of small-area contrast (that which effects picture detail) or large-area contrast. Since small-area contrast greatly effects gray scale as well as picture detail, it is the more important. A principle mechanism for small-area contrast reduction is halation. Halation, as seen in Figure 5, illuminates areas of the phosphor screen which are supposed to be dark with light from luminescing phosphors which reflects off the inside surface of the CRT faceplate, or screen.

The halation effect can be dramatically reduced by coupling the CRT and the projection lens with an index-matched liquid (see Figure 6b). This is referred to as optical or liquid coupling. The benefits in improved contrast and grey scale rendition far outweigh the costly liquid-filled coupler system in most rear-screen systems. In front screen systems, however, the use of optical coupling is more difficult. Wanting to retain the flexibility of choosing a range of screen sizes and magnification, front screen projectors usually employ air coupling so that Scheimpflug corrections can be made easily and without component alterations.

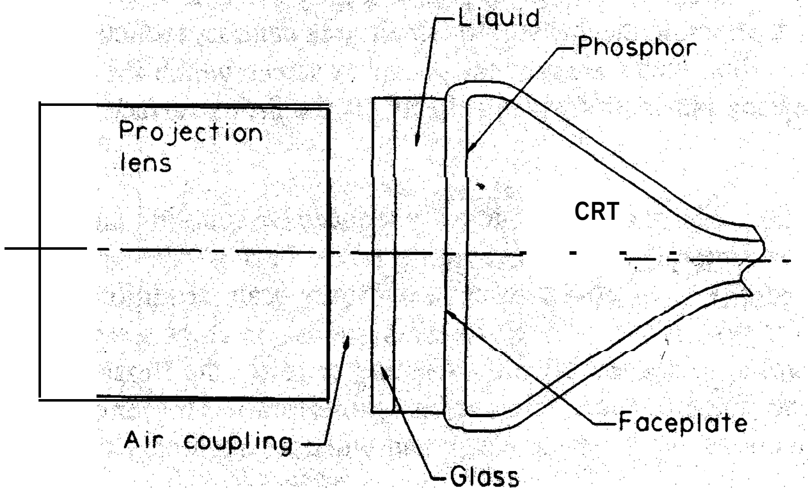
Life

CRT life, for all practical purposes, distills down to cathode life and phosphor life. The cathode life is primarily effected by cathode loading or cathode current density. Specifically, oxide cathode life is optimized at about .3 A/cm^2 due to temperature effects (.. .the cathode life is enhanced if the cathode operates between 1000 and 1130 degrees K). Phosphor life decreases as a function of electron bombardment, The amount and rate is unique to each phosphor. The life of the phosphor is also effected by the tube diameter. The time for the tube brightness to decay by 50% for a 12" tube operated at 200 micro-amps (.3 A/cm^2) may be 18,000 hours, while a 5" tube operated at the same current would only take 1,500 hours to decay to this 50% value. The smaller display would, however, operate at twelve times the luminance of the larger display.

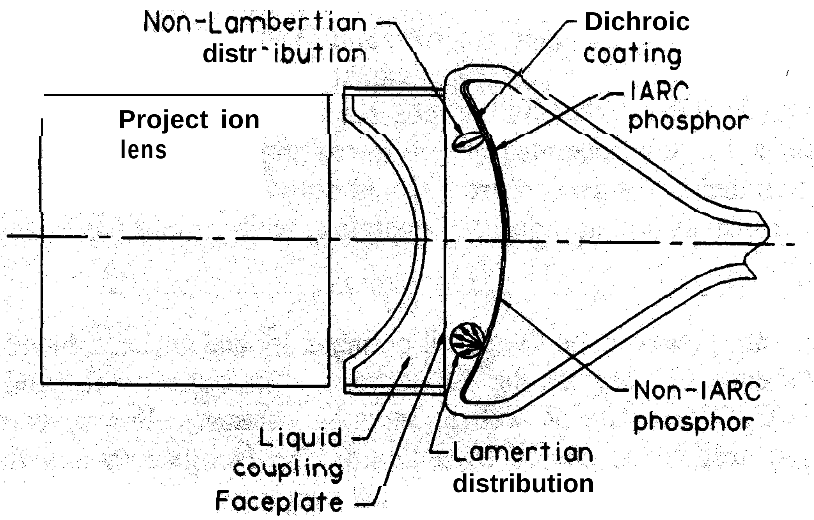
CRT life can, however, be shortened prematurely and catastrophically by thermal tube damage caused by excessive heat on the CRT screen; The optically-coupled CRT-lens design helps to cool the CRT faceplate as well as increase contrast. For air-coupled designs, the faceplate may also need to be cooled by a liquid.. To facilitate this,' a flat plate sandwich structure can be created to contain the liquid, as shown in Figure 6a.

Resolution

CRT resolution is principally determined by two factors--the current density distribution of the electron beam at the phosphor plane and the phosphor itself. Assuming that the phosphor "spot" which is energized by the electron beam is Guassian in nature (as is the beam distribution), then the resolvable spot size is determined by contrast, or MTF limits. This is illustrated in Figure 7.



a. l iquid cooled tube used with air coupled lens



b. opticatty (liquid) coupled tube

F igure 6. Air coupled and opt ically coupled projection lenses

If the objective is 50% MTF, and if the ratio of the width to the peak separation is approximately 0.7 at 50% modulation, then for a .1 mm spot (about the best currently achieved in projection CRT's) the peak separation could be .14 mm. For a CRT of 80 mm height (5.25" diagonal), this would yield 80 mm/.14 mm peak separation, or 570 cycles (1140 TV lines) resolution. This would be very adequate for HDTV and various data and graphics modes. However, as the beam moves off-axis, the spot quality degrades significantly. The relationship between spot size and TV resolution is shown in Figure 8.

Color CRT

The color produced by the CRT is obviously a function of the phosphor chosen. Unfortunately, the phosphors are not monochromatic. In order to improve colorimetry, various coatings and filters are employed to reflect or absorb light of unwanted wavelengths. A representative sampling of red, green, and blue CRT spectral emission plots are shown in Figures 10-12.

Curved Phosphor

Most CRT's used in projection TV today have flat screens or faceplates. The advantage of flat faceplates over curved-input faceplates include simplified mechanical tolerancing and reduced componentry for convergence. The single most important advantage of curved faceplate CRT's is the increased comer illumination. This stems from the Lambertian nature of the light emanating from the phosphor surface. A dichroic coating can be designed to reflect back light of unwanted wavelengths, but more importantly, it can narrow the light distribution (vs. lambertian) to help place light into the pupil of the lens. While overall brightness can be improved as much as 40%, the comer illumination can be increased even more. This last combination of curved input faceplate with dichroic coatings is referred to as the "IARC" tube (see Figure 6b).

Sizes

CRT's for projection TV are available in three principle raster (useable phosphor) diagonals: the 5", 5.75" and the 7". The corresponding tubes are referred to as 7", 8" and 9", respectively.

The Screen

Projection TV screens can be categorized simply into two types, front-screen and rear-screen. In both cases, various features and techniques are used to enable the viewer to experience the best projected image possible.

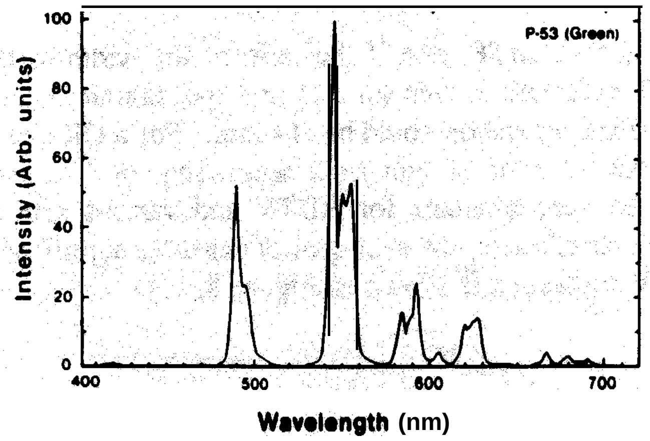


Figure 9 Spectral plot of P-53 green phosphor*

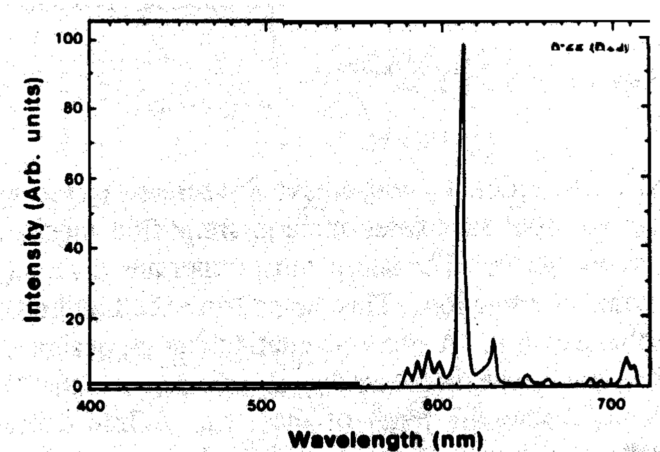


Figure 10 Spectral pl-22 red phosphor*

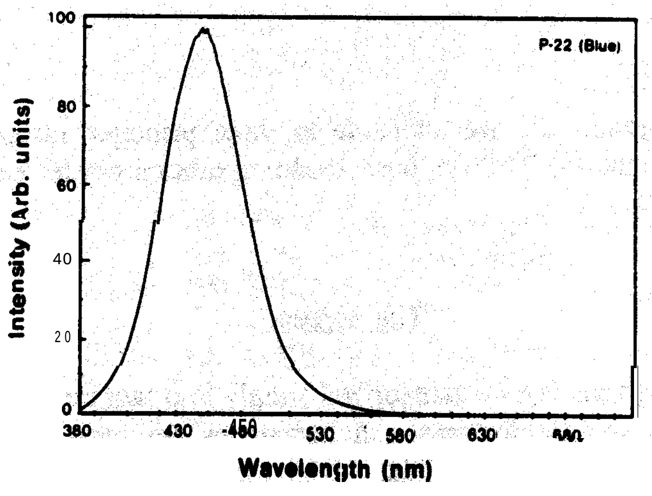


Figure 11 Spectral plot of P-22 blue phosphor *

* Figures 9- 11 are reproduced from Sony Projection CRT General Catalog

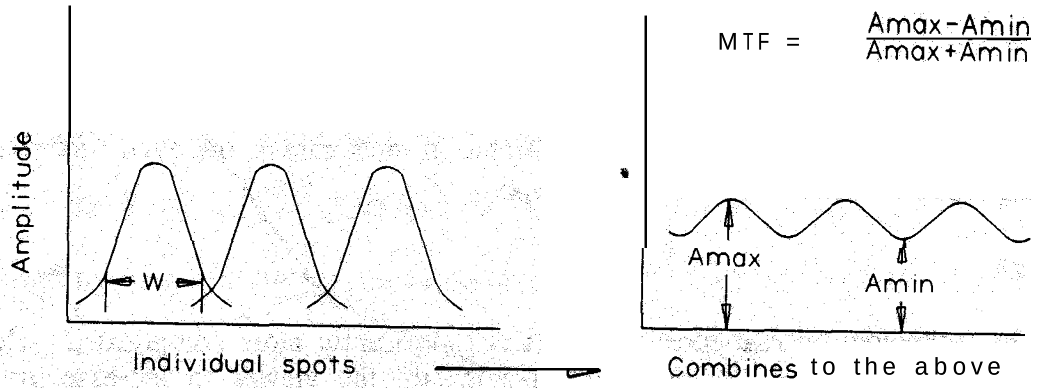


Figure 7 MTF and resolvable spot size

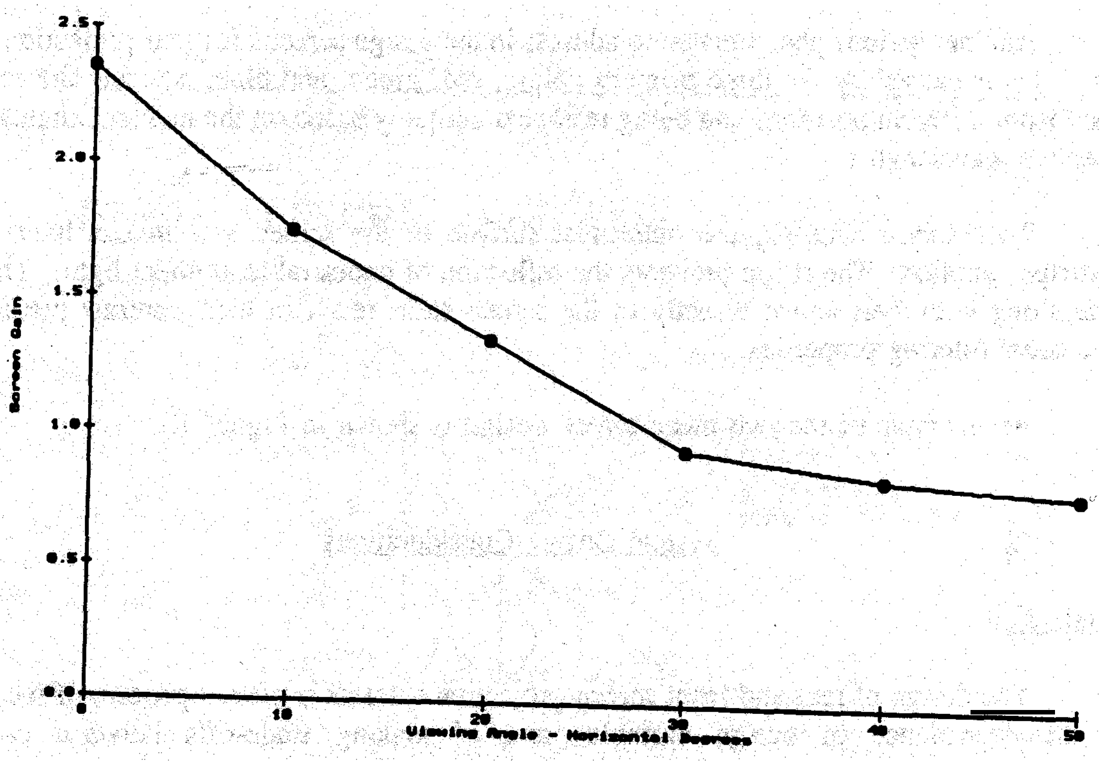


Figure 8 Front screen gain vs viewing angle for the Stewart Ultramatte 250 screen

Front Screen

The trade-offs with the design of front screen systems are between viewing angle, gain (brightness) and screen shape (flat versus curved). For most high-brightness projectors, a screen gain of 2.0 (relative brightness) is recommended with a flat screen. Because of the increased gain on axis, the gain off axis is reduced (see Figure 12).

A technique to maintain high comer brightness with high gain screens (up to 12) is to curve the screen inward toward the viewers. The negative of a high gain, curved screen is the difficulty in mounting (requires a stand-alone frame in most cases), the even further reduced viewing angle and the tendency to have a hot spot.

Rear Screen

The technology in rear-screen systems is significantly more complicated. Here, the objective is to first, refract the projected rays toward the viewer to increase brightness. Subsequently, the rays are refracted back out in the horizontal direction only to improve viewing angle. The way this is done is through both Fresnel and lenticular lenses built into the screen themselves.

Another serious phenomenon to address in the design screens for rear projection is color shift. This is caused by the three primary colors, red, green, and blue, entering the refracting screen from different positions and being refracted uniquely based on the incident angles and the respective wavelengths.

To enhance contrast, the outermost surface of the screen system can have a black "pinstripe" applied. The stripe prevents the reflection of undesirable ambient light. This black stripe along with dyes added directly to the screen resin result in high contrast pictures with some color filtering properties.

An example of the two-piece screen design is shown in Figure 13.

System Design Considerations

Introduction

The design of rear and front screen projection systems is often a process of recognizing the interdependence of design variables and of making trade-offs between conflicting requirements. Certain methods for making these trade-offs have proven effective in the past, and a great deal of what follows is based on these tried and true principles. However, in practice every projection system design must be considered for its own unique application and requirements. This approach has led to many of the improvements and advances which have been made in the field over the last several years.

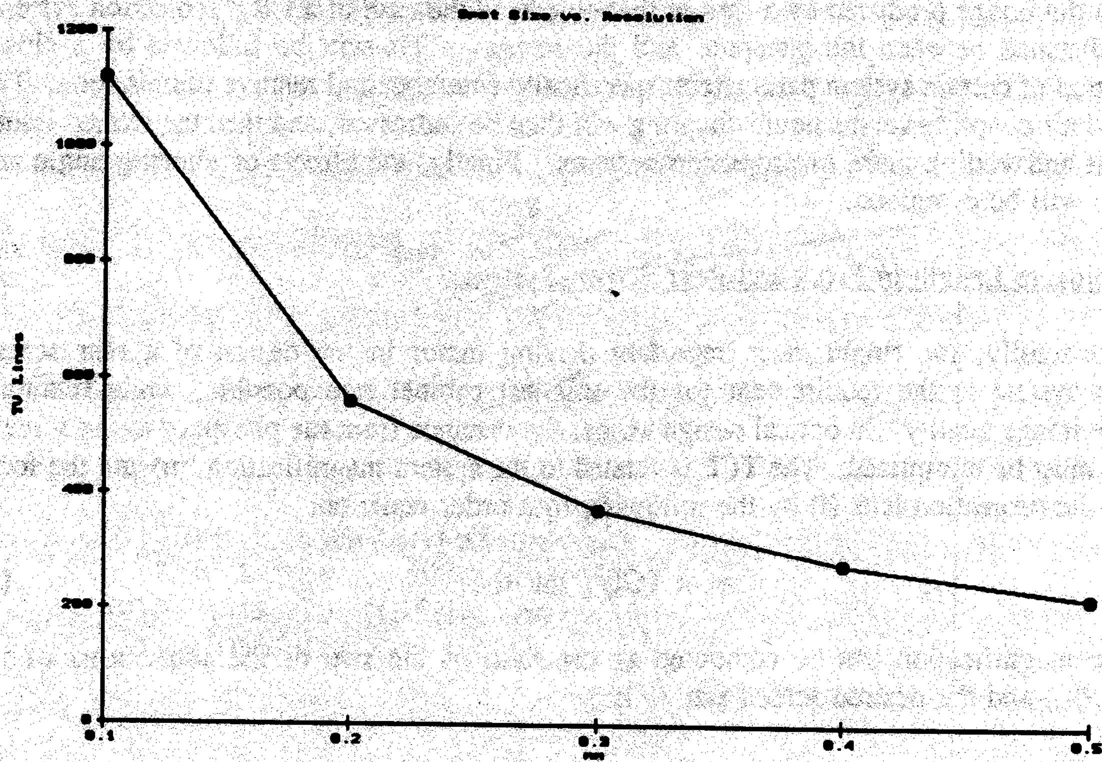


Figure 12 CRT spot size vs resolution

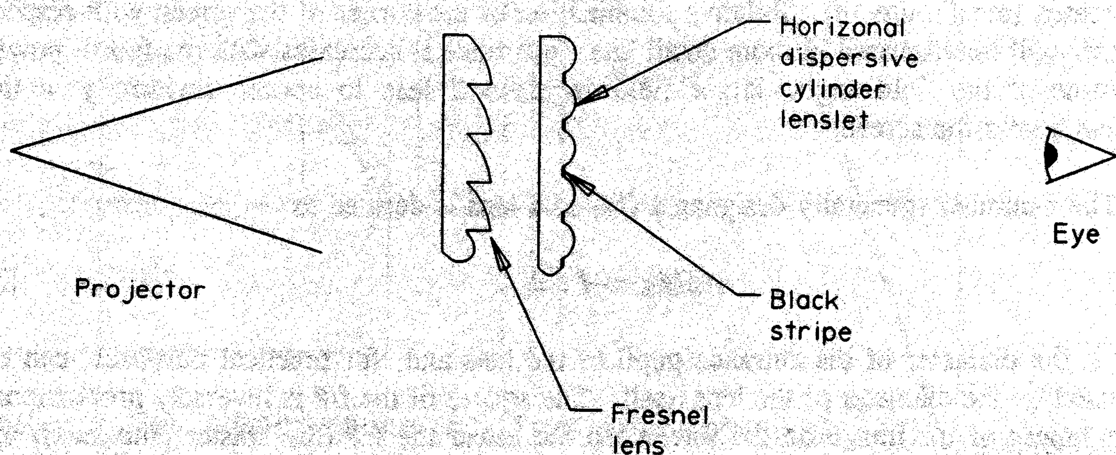


Figure 13 Top view of two piece screen

In order to illustrate the type of logic which is followed in the' design of an optical projection system, the effect of one optical parameter, the total conjugate length (TCL), will be considered for both rear screen and front screen systems. The TCL is the distance between an object and the image produced by a lens of that object; in the case of a CRT projection system, it is the distance between the phosphor and the screen. This will be followed by a closer consideration of certain system parameters, specifically f-number and relative illumination. The question of air coupling versus liquid coupling will then be addressed, and then the related issues of contrast and veiling glare in projection systems. Finally, the effects of viewing angle and color shift will be examined

Total Conjugate Length in Front and Rear Screen Systems

Generally, the single most important driving factor in the design of a rear screen projection system is the requirement for the smallest cabinet size possible, while retaining acceptable image quality. In optical design terms, the distance from the phosphor to the screen, the TCL, must beminimized. The TCL is related to the system magnification (m) and the focal length of the projection lens (f) by the following first order equation:

$$f = m\, TCL / (m + 1)^2, \tag{2}$$

where the magnification can be computed as the ratio of the size of the active area of the phosphor (h,) and the desired screen size (h_s):

$$m = h_s / h_p$$

So equation 2 states that for a given magnification, the focal length is directly proportional to the TCL; the shorter the TCL required, the shorter will be the focal length of the projection lens.

For a given CRT and screen size, as the focal length decreases, the projection field angle increases (see Figure 14). Relative illumination of the comer of the screen with respect to the center will be discussed in more detail later, but since it decreases with the fourth power of the cosine of the field angle, larger field angels will lead to poorer uniformity in the illumination across the screen.

The f-number (generally designated f/#) of a lens is defined as

$$f/\#_\infty = f / d_e \tag{3}$$

where d_e is the diameter of the entrance pupil of the lens and, for practical purposes, can be approximated by the diameter of the lens itself. The square of the f/# is inversely proportional to the brightness of the image on the screen, so the lower the f/# (the "faster" the lens), the higher the screen brightness. For rear screen projection systems, a commonly accepted goal is an f/# of unity (f/1.0). Since the focal length is to be made a small as possible for rear screen systems in order to reduce the TCL, it can be seen from equation 3 that the diameter of the lens

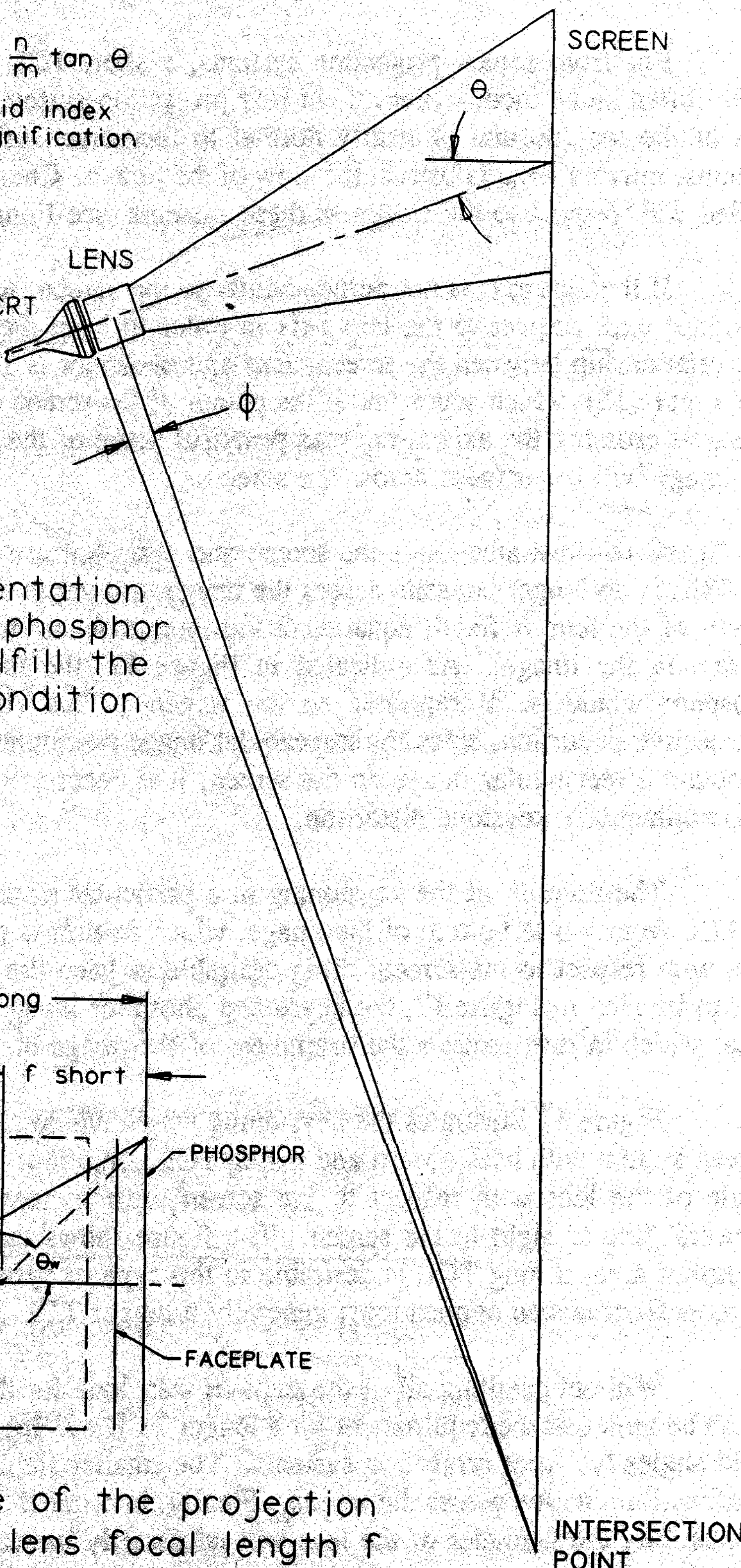


Figure 15 Orientation of the screen, phosphor and lens to fulfill the Scheimpflug condition

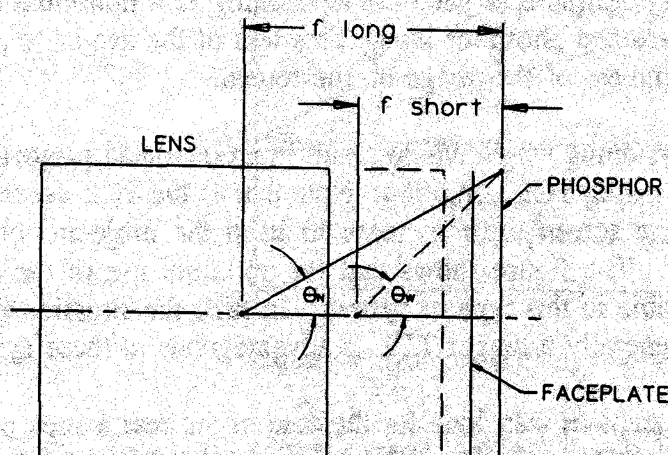


Figure 14 Dependence of the projection field angle θ on the lens focal length f (f long = θ narrow f short = θ wide)

will decrease proportionately. In effect, this means that lenses for rear projection systems will tend to be small, which may have a beneficial effect on the cost of the lens itself.

For front screen projection systems, a short TCL is not a requirement and, in fact, would often be an inconvenience. In rear projection systems, it is possible to make the optical axis of the lens normal or nearly normal to the screen using mirrors. But for front screen systems, mirrors would obstruct the view of the image. Consequently, the lens axis is invariably angled with respect to the screen in these systems (see Figure 2b).

If the lens axis is not perpendicular to the screen, it is necessary to tilt the plane of the phosphor with respect to the lens axis in order to keep the image in focus across the screen, The relationship between the screen, lens and phosphor is given by the Scheimpflug Condition (see Figure 15), which states that if the planes of the screen and phosphor and the normal to the lens axis crossing the axis at the rear principal plane of the lens all intersect in one point, then the image will be in focus across the screen.

As Figure 16 illustrates, once the screen and phosphor are tilted with respect to the lens axis, the TCL is no longer constant across the image, but varies from top to bottom. Since the focal length of the lens is fixed, equation 2 indicates that the magnification must vary from top to bottom in the image. As indicated in Figure 17, the image of a perfect rectangle on the phosphor would be a trapezoid on the screen. This effect is known as “keystoning” or perspective distortion, since the trapezoidal image resembles the keystone in an arch. In order to obtain a rectangular image on the screen, it is necessary to give the image on the phosphor a complimentary keystone distortion.

The severity of the keystoning in a particular situation is proportional to the variation in TCL from top to bottom of the image, which in turn is proportional to the angle of the lens axis with respect to the screen. It is desirable to keep the keystoning to a minimum because, as can be seen in Figure 17, the keystoned phosphor image uses less of the available phosphor area, which in turn reduces the brightness of the image on the screen.

Figure 17 illustrates the keystoning which would result in an overhead projection front screen system with both a short and a long TCL condition. Note that as the TCL decreases, the angle of the lens with respect to the screen must increase to keep the projector out of the viewers’ line of sight to the screen. The figure shows that for optimum use of the available phosphor area, a long TCL is desirable in this type of system. In fact, the situation is similar in most front screen applications; generally a longer TCL is advantageous in these systems.

Without detailing all of the steps as was done for the case of the rear screen projector, it can be seen that the requirement for a longer TCL will lead to longer focal lengths and smaller field angles for front projection systems. The smaller field angles will lead to a more uniform relative illumination across the screen. Finally, in order to keep the f-number of the lens as low as possible, the diameter of the lens will necessarily increase, which may increase the cost of this type of lens.

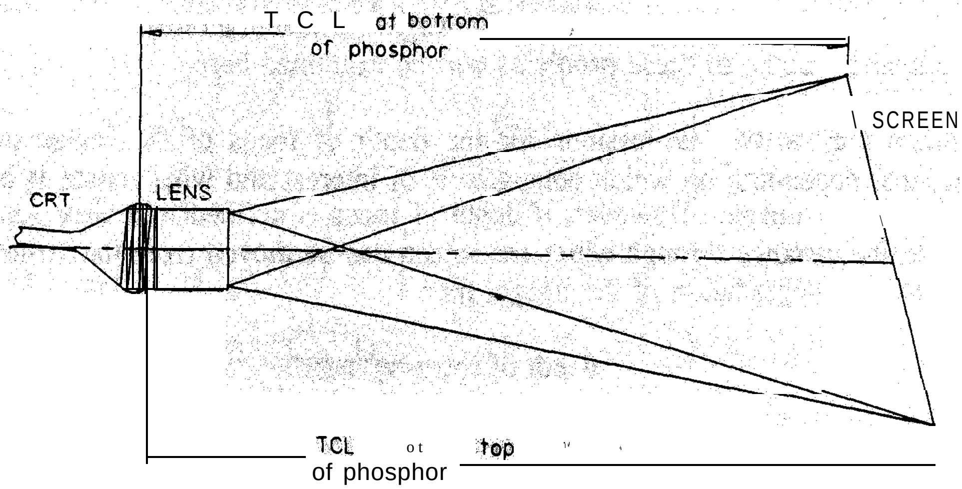


Figure 16
TCL varation across phosphor with the Scheimpflug condition.

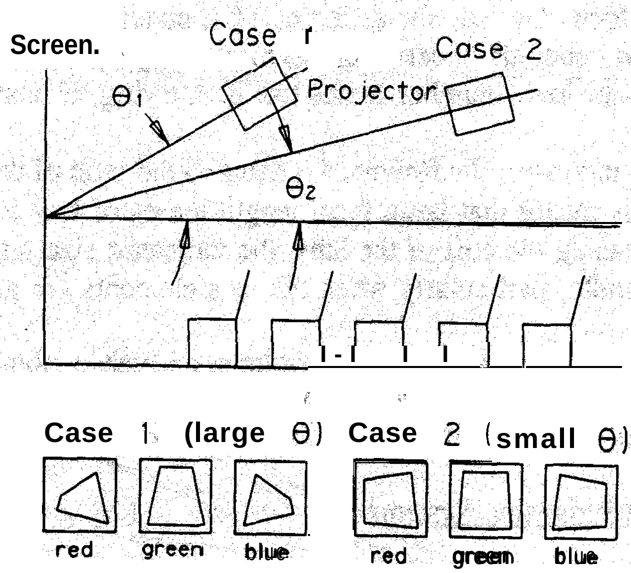


Figure 17
Keyston ing for short and long TCL.

f-Number of the Proiection Lens

As has been stated in the previous section, it is desirable to minimize the f-number of the projection lens in order to maximize the brightness of the image on the screen. However, low f-number lenses pose certain problems in design and manufacture, both of which affect the cost of the lenses. Some of these problems will be examined here.

There are various expressions for the depth of focus of the image produced by a projection lens, depending on which conjugate is of interest and what sensor is being used for the detection of the image. However, if depth of focus is defined in a very general sense by equating it to the distance through which the screen can be moved from the "true" image plane without noticeable degradation of the image, then

$$\text{depth of focus} \propto f/P.$$

Consequently, the lower the f/# of the lens is the shallower is the depth of focus of that lens.

From a mechanical point of view, the reduced depth of focus puts tighter requirements on the focus mechanism for the lens. If the lens is focused using a thread which translates the whole lens, then this thread must be fine and care must be taken in the mechanical design to ensure that the thread allows no lens tilt. Often the lens focus is achieved by shifting elements mounted in an inner barrel with respect to an outer barrel (see Figure 18). In this case, the slot in the outer barrel must be cut at a shallow angle for a low f/number lens so that the inner barrel shift is slow and not overly sensitive. This can be a problem mainly in lenses designed to operate over a range of magnifications, since the same slot is used to shift the power group significant distances to focus the lens for different TCL conditions. Finally, for high volume consumer systems where hundreds of sets must be focused by the same person on a daily basis, the small depth of focus of low f/number lenses can be a trying, if unavoidable, circumstance.

As equation (3) indicates, the f/number is equal to the ratio of the lens aperture diameter to the focal length. This means that large focal length lenses of low f/number will be large in diameter. Resides increasing the cost of the lens, the increased size will make the lens heavier and more difficult to handle, particularly when the lens elements are glass.

To summarize, the increase in image brightness which is obtained with low f/number lenses is paid for with a significant tightening of optical and mechanical design requirements. Obviously, at some point the price becomes too high to pay.

Relative Illumination in Proiection Systems

The relative illumination at a point P in the image field is defined as the ratio of the illumination at P to the illumination on axis (see Figure 19). From consideration of the angular emission of the source (assumed Lambertian) and the angular orientation of the object and image planes with respect to the lens axis, it can be shown that

$$\text{Relative Illumination} = \text{RI} = A, \cos^4 \theta_P$$

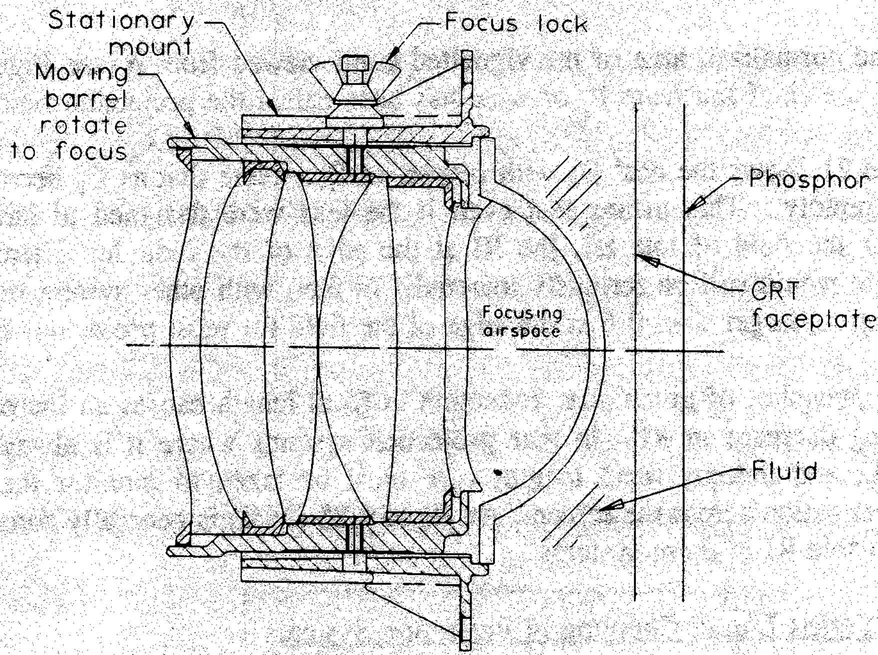


Figure 18
Focusing performed by shifting barrel mounted elements in a focus mount

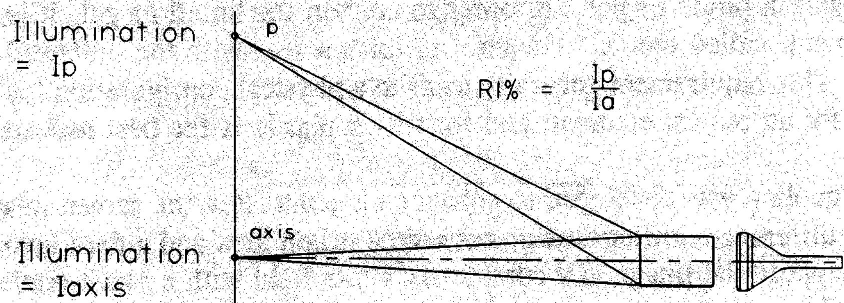


Figure 19
Relative illumination (RI) at a point P off axis in the image plane

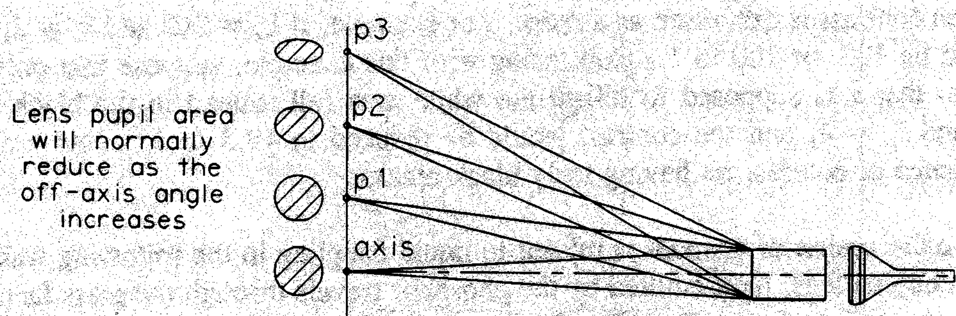


Figure 20
Normalized pupil area for various positions in the image plane

where A_p is the normalized area of the vignetted pupil viewed from p (see Figure 20) and Θ_P is the angle of the chief ray from P, or what has been called the projection field angle.

Figure 21 shows the $\cos^4 \Theta_P$ with respect to Θ_P. Note that as Θ_P becomes large $\cos^4 \Theta_P$ decreases rapidly. This means that even if the lens were designed to have no aperture vignetting over the field of interest, the RI at the edge of the field for a lens with a large projection angle would still be seriously lowered. In fact, with other system restrictions, it is difficult to keep A_p larger than 0.6 at the edge of the field for most projection systems.

For a phosphor of given size, reduction in focal length causes an increase in Θ_P, and a corresponding decrease in RI. In rear projection Systems where it is always important to minimize TCL, and thereby focal length, care must be taken to monitor the RI to ensure acceptable illumination across the screen. An RI of 0.25 (25%) is generally considered a lower limit for acceptable RI in these systems.

Air Coupling Versus Liauid Coupling in Projection Systems

Figure 6 shows the distinction between an air coupled lens and an optically coupled (liquid coupled) lens. In an air coupled lens, there is an airspace between the last optical element in the lens and the front surface of the CRT faceplate. In an optically coupled lens, this airspace is filled with a liquid or gel. In order to contain the liquid or gel, it is necessary for the final lens element, called the "C" element, to form a seal with the bulkhead on which the CRT is mounted. This requirement generally leads to a physical configuration for the C element which is unusual for an optical element, and for which plastic is the best material.

Optical coupling was developed to enhance the contrast in the screen image. Contrast, simply put, is the difference in illumination between a bright area and a dark area in the image. As an example, suppose the image is a completely white field with a black circle in the center (see Figure 22). To measure contrast, the illumination of the image is measured in the white area immediately adjacent to the dark are (I_w), and then measured in the center of the dark area (I,,). Then the contrast is given by

$$\text{Contrast} = I_w / I_b.$$

Most often contrast is expressed as a ratio. For example, if I,,,, = 200 and I,, = 2, then the contrast would be 100, or 100 to 1. Continuing with this example, suppose that only 1% of the illumination that was supposed to fall in the white area fell instead in the black area. Then I_w = 198 and I_b = 4, and the contrast would be reduced to 49.5 to 1. This example shows the dependence of contrast on having truly black blacks.

The above discussion of contrast is related to liquid coupling in the following way. In the case of an air coupled lens, light emitted by the phosphor travels through the glass faceplate and reaches the air/glass interface. Fresnel reflection takes place at this interface, with about four percent of the light reflecting from the interface and traveling back toward the phosphor and ninety-six percent of the light transmitting through the interface. The reflected four percent will strike the phosphor, which is white and an excellent scatterer of light. Now the whole face of

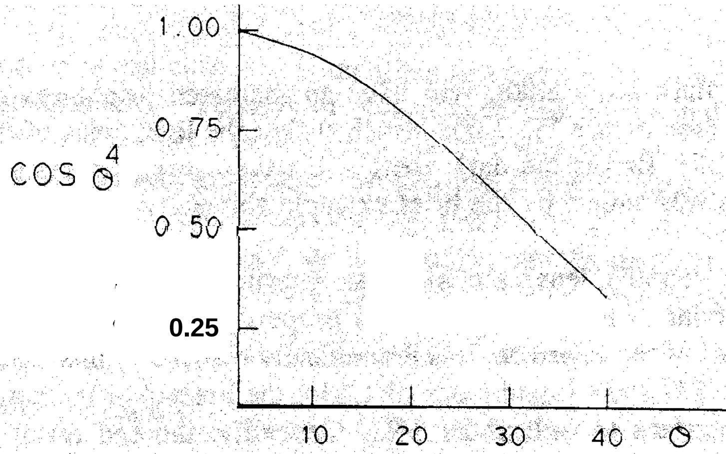
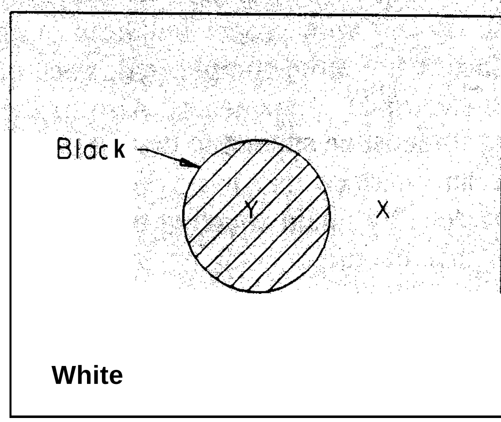
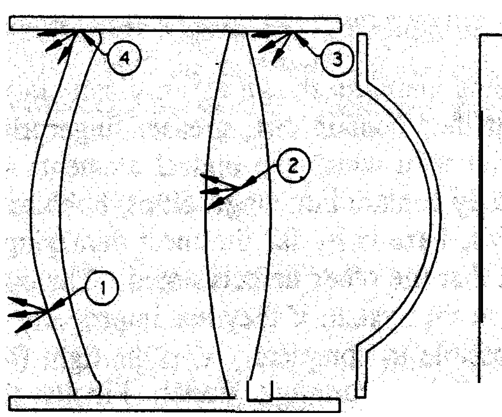


Figure 21 Cos Θ^4 falloff not including pupil area



X = White measurement position
Y = Black measurement position

'Figure 22 Measurement of contrast



1) Optical Surface
2) Material
3) Mount
4) Element Edge

Figure 23 Sources of Veiling Glare

the phosphor, light and dark areas alike, will have an increased brightness due to the light reflected at the interface (see Figure 5). Light which strikes the light areas of the phosphor are unimportant, but that which strikes the dark areas will have a very detrimental effect on the contrast in the image, as was shown by the brief example above.

In an optically coupled lens, the air/glass interface is replaced by a liquid/glass interface. Since the amount of Fresnel reflection is proportional to the difference in index of refraction on the two sides of the interface, it is dramatically reduced in this case. For example, for a faceplate index of 1 .537 and a liquid index of 1.443, the Fresnel reflection is reduced from the 4% of a -glass/air interface to well under 1%. Generally, the end result in terms of the contrast measured on the screen is on the order of a fortypercent improvement in contrast.

There are other consequences of using a liquid coupled lens. On the positive side, there is no need for a liquid cooled tube if a liquid is used for the optical coupling, since the coupling fluid itself can serve as the coolant with proper bulkhead design. On the negative side, the bulkhead design and manufacture are more complicated, since a liquid must be dealt with in an area invariably packed with electronic components. Also, if the lens axis is tilted with respect to the screen, a Scheimpflug tilt must be applied to the CRT, and in the liquid coupled case, this tilt must be applied across an interface that has a liquid-tight seal. However, the dramatic improvement in contrast afforded by liquid coupling outweigh the disadvantages in the opinion of many projection system manufacturers, judging by the number of systems on the market which utilize this feature.

Veiling Glare in Projection Systems

Veiling glare is another effect which can have a dramatic effect on the contrast of a projection system. Veiling glare is non-imaging light from the source which is scattered by the optical system and uniformly illuminates the screen. Continuing with the example used above, suppose that $I_w = 200$ and I, = 2, giving a contrast ratio of 100 to 1. Now suppose that only one unit of non-imaging light is scattered by the system uniformly across the screen. In this case, $I_w = 201$ and I, = 3, giving a contrast ratio of 67 to 1. Very little veiling glare can have a very significant effect on image contrast.

The sources of veiling glare are shown schematically in Figure 23. Optical surfaces are sources of scattered light if they contain dirt, grease, fingerprints, scratches, or imperfect or hazy coatings. The material with which the optical elements are made, glass or plastic, are sources of veiling glare if they contain inhomogeneities, bubbles, inclusion, or haze. Note that in both of the above sources, haze is by far the most damaging problem, since it tends to be exhibited over larger areas that the other defects noted. The edges of optical elements can be a source of scattered light in the system if they are improperly stopped with mount apertures. In cases where it is not possible to completely stop the light from an element edge, the edge must be painted a flat black, light-absorbing material. Finally, the mount itself can be a source of scattered light if stops and anti-reflection threads are improperly designed or if internal surfaces are not effectively blackened.

There is no universal cure for veiling glare in a system. Its sources are many, and they must be pursued individually. Vendors of optical materials must supply clean material. The fabrication of the optical surfaces and coatings must be flawless, and subsequent handling and storage must be performed with great care. Mounts and element edges must be designed to stop all non-imaging light which enters the system; there are several optical design programs commercially available which can aid in this design, not to mention the many proprietary programs in use. Only through constant attention to all of these areas can veiling glare be reliably controlled.

Viewing Angle and Color Shift

Figure la is a diagram of a three-tube projection system. Note that all three channels, green, red, and blue, have a different angle of incidence with respect to the screen. Figure 24 shows angular dispersion patterns of the light transmitted by the screen for each channel. Ideally, these patterns would overlap, so that a viewer would receive the same proportion of each color regardless of his viewing position. Since the angular dispersion patterns do not overlap, the relative color mix will vary depending on the angle of the viewing axis with respect to the screen. This dependence of the color mix on viewing angle is known as color shift.

Color shift can occur in both rear screen and front screen systems. In fact, any multi-channel optical system where the different channels take different optical paths to the screen is subject to this problem. There are basically two ways to approach the color shift problem.

First, and as a general rule, the angle of incidence of the various channels with respect to the screen should be made as constant as possible. This design principle will not only' minimize the color shift problem, but also will ensure optimum phosphor coverage for the different colors and greatly reduce convergence problems in the final set.

Second, some means can be taken to ensure that the angular dispersion of the light which is scattered by the screen is constant regardless of the angle of the light incident on the screen. In front screen systems, this can be accomplished by manipulating the gain of the screen, as was indicated in the section concerning screen design. For rear screen systems, the design of the different screen "layers" (see Figure 13) is manipulated to attempt to bring the three channels into coincidence. However, the problem is a difficult one, and every attempt should be made to minimize the difference between the incidence angles of the three channels to the screen when possible.

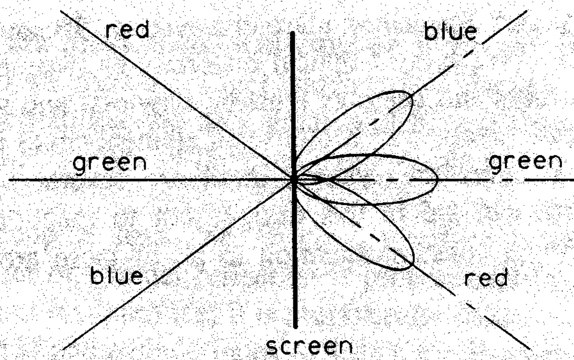


Figure 24 Angular dispersion of the three colors in a rear screen system

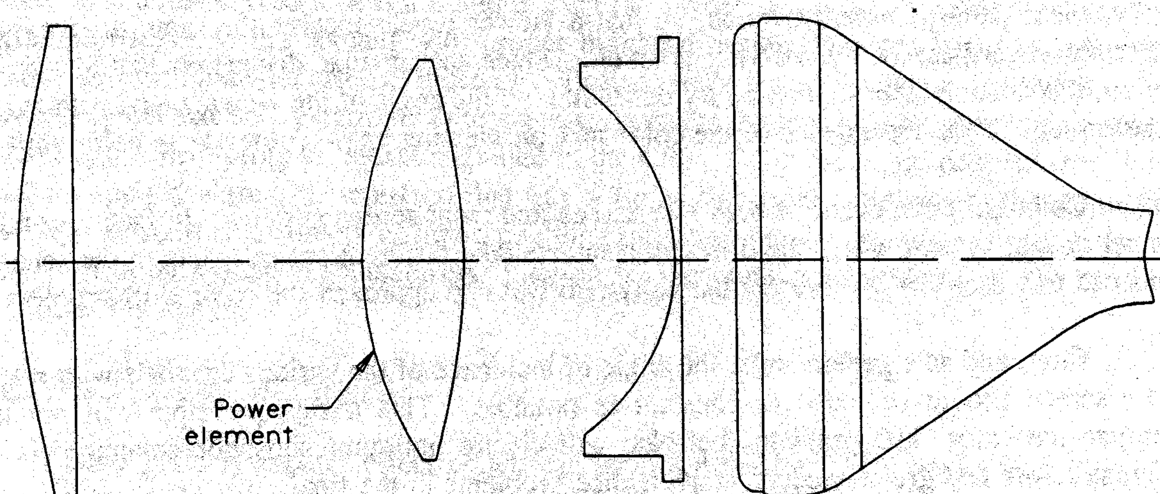


Figure 25 The original Delta design, all plastic material for elements & extensive use of aspheres

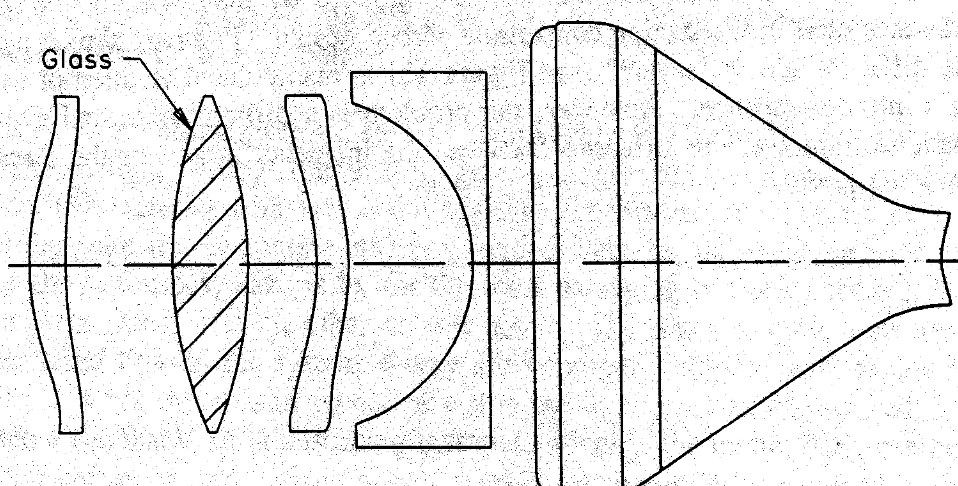


Figure 26 The Delta lens with a glass power element and extra aspheric plastic element

Optical Performance Requirements

To evaluate the image quality of a lens it is preferable to specify and measure the MTF of the lens at one or more spacial frequency. Various system parameters like the source material bandwidth, the CRT spot size, the spectral range of phosphors, the angular resolution of the viewer's eye, and others may be used to determine the required optical performance of the lens. The typical MTF design targets are given in Table 3.

Table 3 MTF Design Goals for Various Applications

	MTF	SPATIAL FREQUENCY
Consumer Application (NTSC, PAL, SECAM)	80%-85%	2 lp/mm
HDTV	85 %-90%	2 lp/mm
	50%	6 lp/mm
DATA/GRAPHICS	85%-90%	2 lp/mm
	50%	10 lp/mm

Note that the spatial frequency of 2, 6 and 10 lp/mm corresponds to 4, 12, and 20 TV lines/mm. These performance targets are used at all points across the image format.

Some Of the Lens Forms for Projection TV Applications

Today's lenses for projection TV applications must satisfy a wide range of difficult requirements like a high speed, a wide field of view, a high relative illumination, a high level of image quality, a variety of system-specific requirements, and, last but not least, a cost low enough so as to make the whole system a commercially viable product. It is this, the last requirement, that provided an impetus in developing the original "DELTA" lens (see Figure 25).

To achieve a speed approaching f/1 and a field of view of 45° to 50" using just spherical surfaces would require a lens with about 6 elements. The original DELTA made use of aspherical surfaces and a unique configuration to achieve the same goal in three elements. However, aspherical surfaces on glass are very expensive to manufacture. Using optical plastics, even with the initial tooling expenses, aspherical lenses are much more affordable than comparably performing all-glass lenses. The thermal expansion of plastic materials and the index of refraction variation with temperature may present a problem. When a lens is positioned in front of a hot running CRT, the temperature of the internal elements may increase, Depending on the configuration of the lens and the configuration of the system as a whole, the temperature on the surface of some of the elements may change by as much as 30°C to 40°C. This, in turn, may cause an appreciable change in the focal length of the lens and a correspondingly noticeable focus shift.

It is possible to compensate for this thermal drift of focus by various mechanical means using bi-metal devices or supplementary motors to achieve an appropriate displacement of some of the internal elements of the lens or by moving the lens as a whole. However, since the dominant effect of the change in temperature is the change in the refractive index, the easiest way to minimize this drift of focus is to replace the strongest element or elements in the lens with a more thermally stable material • glass. For economical reasons, surfaces of the glass elements are spherical. Consequently, to achieve the required level of correction of aberrations, it may be necessary to add another plastic aspherical element. A DELTA lens with these modifications is shown in Figure 26.

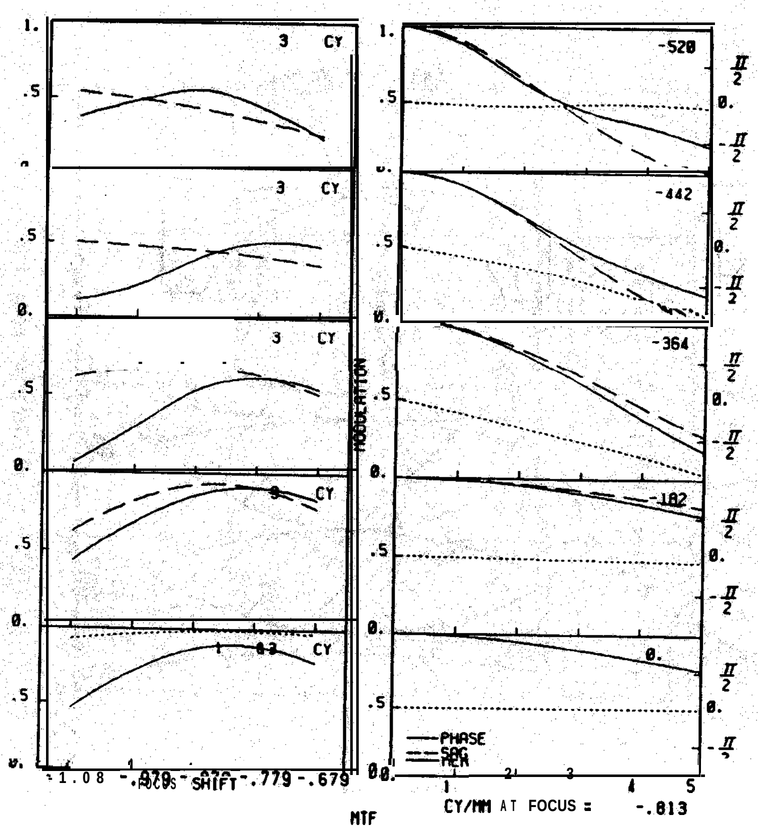
Note that in this form of the lens the strongest element is made out of glass and the rest of the elements are made out of acrylic with a minimum of optical power in each of them. The thermal focus drift of this lens is well under control. Lenses with both plastic and glass elements are called "hybrid" lenses.

To achieve a low lens cost, the most common and easiest to work glasses like BK7, SK5 and, occasionally, SK18 are used. When it is necessary to provide some correction of chromatic aberrations, an F2 flint is used, though often the choice of flints is wider since they do not differ significantly in price.

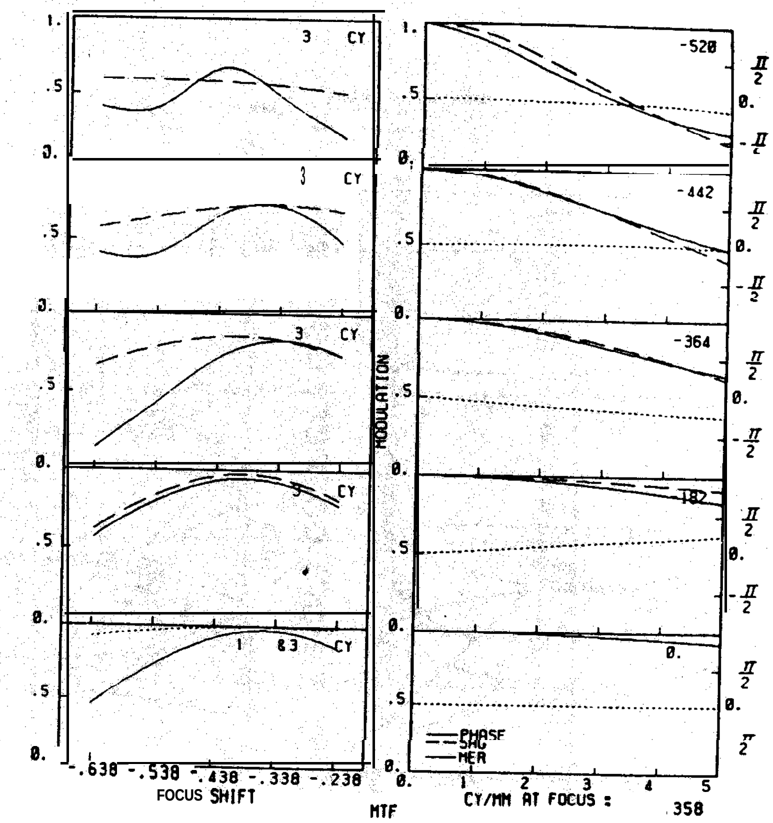
A very important benefit of using an extra aspherical element between the power group and the field flattener is demonstrated in Figure 27. As can be seen from this figure, the MTF at lower frequencies (l-2 lp/mm) throughout the field of view of the lens is appreciably higher in the lens containing the extra element. Using aspherical surfaces between the power group and the field flattener allows better correction of off-axis aberrations, particularly that of sagittal oblique spherical. As a result, the field of view covered by lenses using this configuration can be as high as 72" or more.

As mentioned before, some of the lenses for projection TV provide correction for chromatic aberrations. It is well known that the CRT phosphors are not strictly monochromatic (see Figures 10-12). In fact, the green phosphor may have quite significant red and blue side bands. Therefore, to achieve a better performance, it may be necessary to correct the lens for color. A common lens form capable of providing a high level of correction of aberrations including those caused by the wide spectral range of light emitted by the phosphor is shown in Figure 28. When compared to the lens in Figure 26, this form has two more glass elements, a bi-concave negative element of high dispersion, and a bi-convex positive element of low dispersion, to provide correction for longitudinal color. Figure 29 shows the level of correction of aberrations achieved by lenses in Figure 26 and Figure 29, respectively. As with the lens in Figure 26, this form will cover a field of view of 66" at f/l. Again, most of the Rower is concentrated in glass elements and, as a result, the thermal focus drift does not present a significant problem.

M-7/29



a) **Delta lens with 3 elements**



b) **Delta lens with 4 elements**

Figure 27 MTF curves

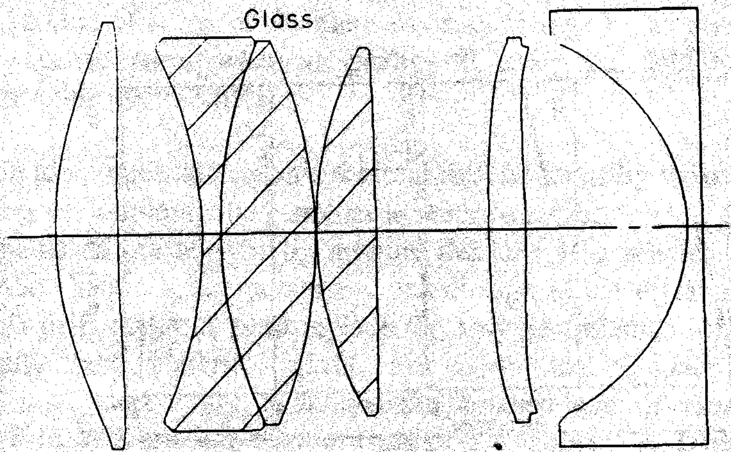


Figure 28 The color corrected Delta lens

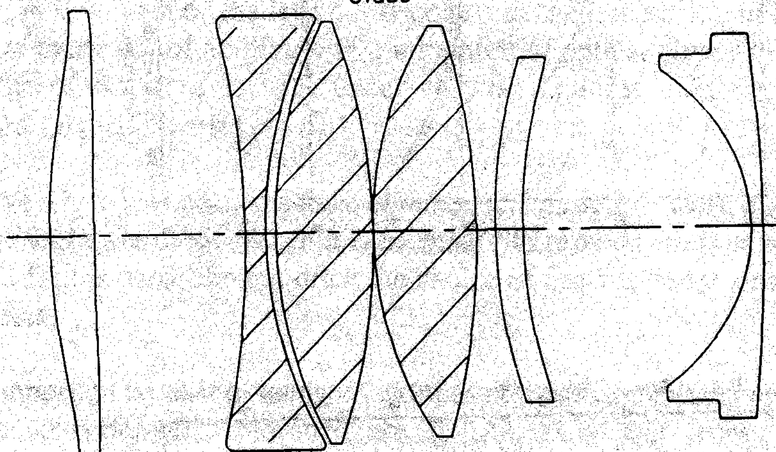


Figure 30 The HD-6 lens

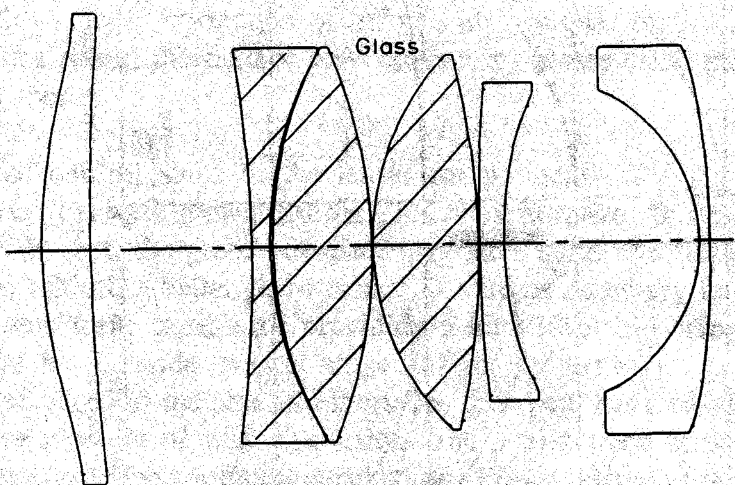
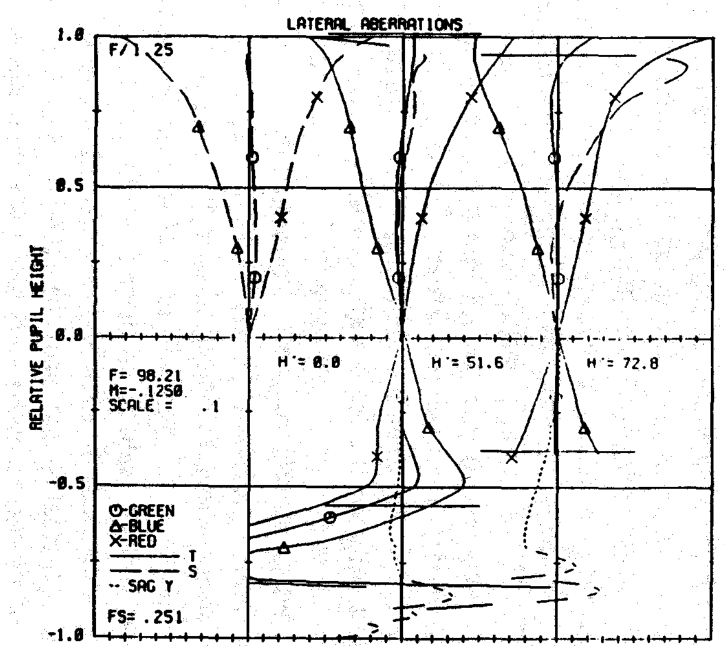
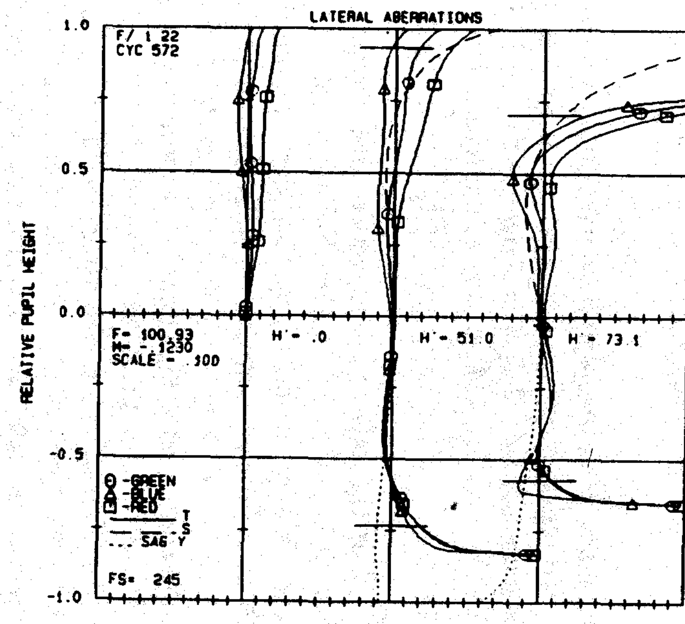


Figure 31 The HD-8B lens



a) Without color correction



b) With color correction

Figure 29 Lateral aberrations for two lenses of similar focal length & speed

With the CRT spot size approaching 0.1 mm, the projection lenses for HDTV and DATA/GRAPHICS applications must have a maximum MTF at 10 lp/mm. The lens shown in Figure 30 is capable of providing this level of performance. It has been sold for a number of years under the name HD-6. The field of view of the lens is 46°, it *covers* 5" raster diagonal on the CRT.

To increase the amount of light and achieve a high resolution on the screen, larger CRT sizes are often used. Consequently, projection lenses must increase their field of view or focal length. In practice, both variables are considered. The lens shown in Figure 31 is the HD-8B lens covering 5.75" raster diagonal on the CRT. The f/number of the lens is f/l. 1 and the field of view is around 52".

The lens shown in Figure 32 is the HD-114'lens which also covers 5.75" raster. However, the focal length of this lens is significantly shorter than the focal length of HD-8B and, consequently, the field of view of this lens at 66" is much wider than the field coverage of HD-8B. In order to accomplish this without compromise in image quality an additional aspherical element is used in front of the lens. Figure 33 shows design MTF for HD-8B and HD-114, respectively. Sometimes, depending on applications, it is more advantageous to add an additional aspherical element or elements behind the power group of the lens. It is important, though, to note that the basic form of the lens remains the same - with the glass elements for thermal stability and color correction in the middle of the lens, the strong negative element next to the CRT to provide necessary correction of field curvature, 'and low power plastic aspherical elements on both sides of the power group to facilitate the appropriate level of correction of various other aberrations.

The size of glass elements in the lenses discussed thus far is large. Indeed, the cost of glass is one of the biggest contributors to the overall cost of the lens. Therefore, it would be desirable to find a lens form which would use less glass and be more economical to produce, but, at the same time, would retain all the advantages of high image quality and good thermal stability. The lens in Figure 34 is capable of achieving a level of optical performance required by HDTV and DATA/GRAPHICS applications. It, too, has a strong negative element next to the CRT to provide for correction of field curvature, a positive power middle group having a combination of positive and negative elements to provide for some correction of chromatic aberrations, and a weaker front group facing the projection screen. However, the front group in this form uses a combination of positive and negative elements.' The burden of obtaining chromatic aberration correction is split between the front and the middle power group. As a result the negative elements in each of these groups do not have to be as strong as the negative element in the middle group of lenses described before. Consequently, it is possible to manufacture these elements out of high dispersion plastic materials' such as styrene or polycarbonate. Using aspherical surfaces on these elements allows for even better control of aberrations. The strongest positive element in the second group is still made out of glass to reduce the thermal focus drift. The further control of thermal drift can be achieved by appropriate combination of powers of individual positive and negative plastic elements of the lens. The overall cost of this lens is appreciably less than the HD-114 shown in Figure 32, mainly due to the fact that the cost of plastic elements will be lower than the cost of glass elements.

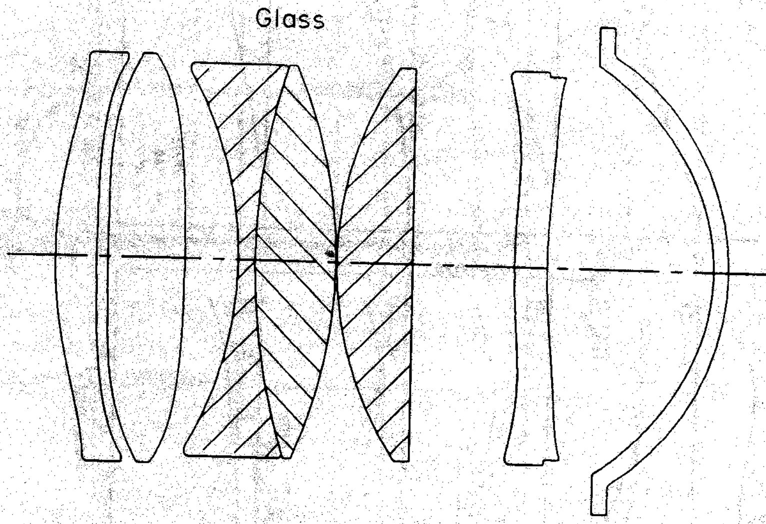
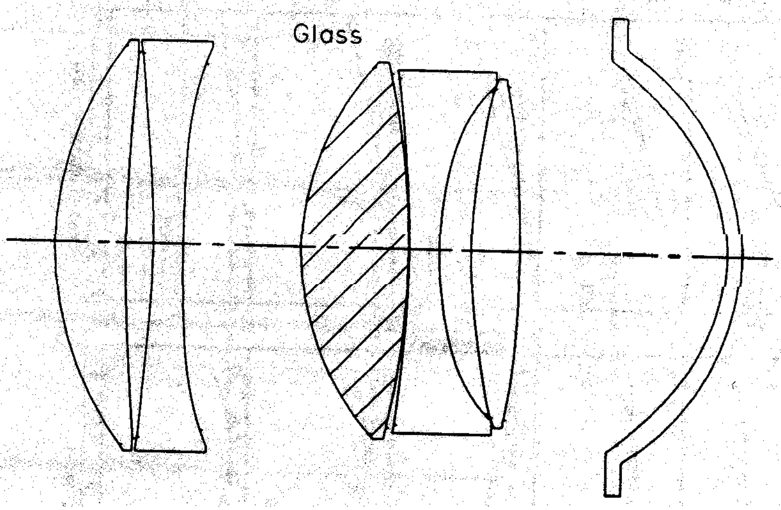
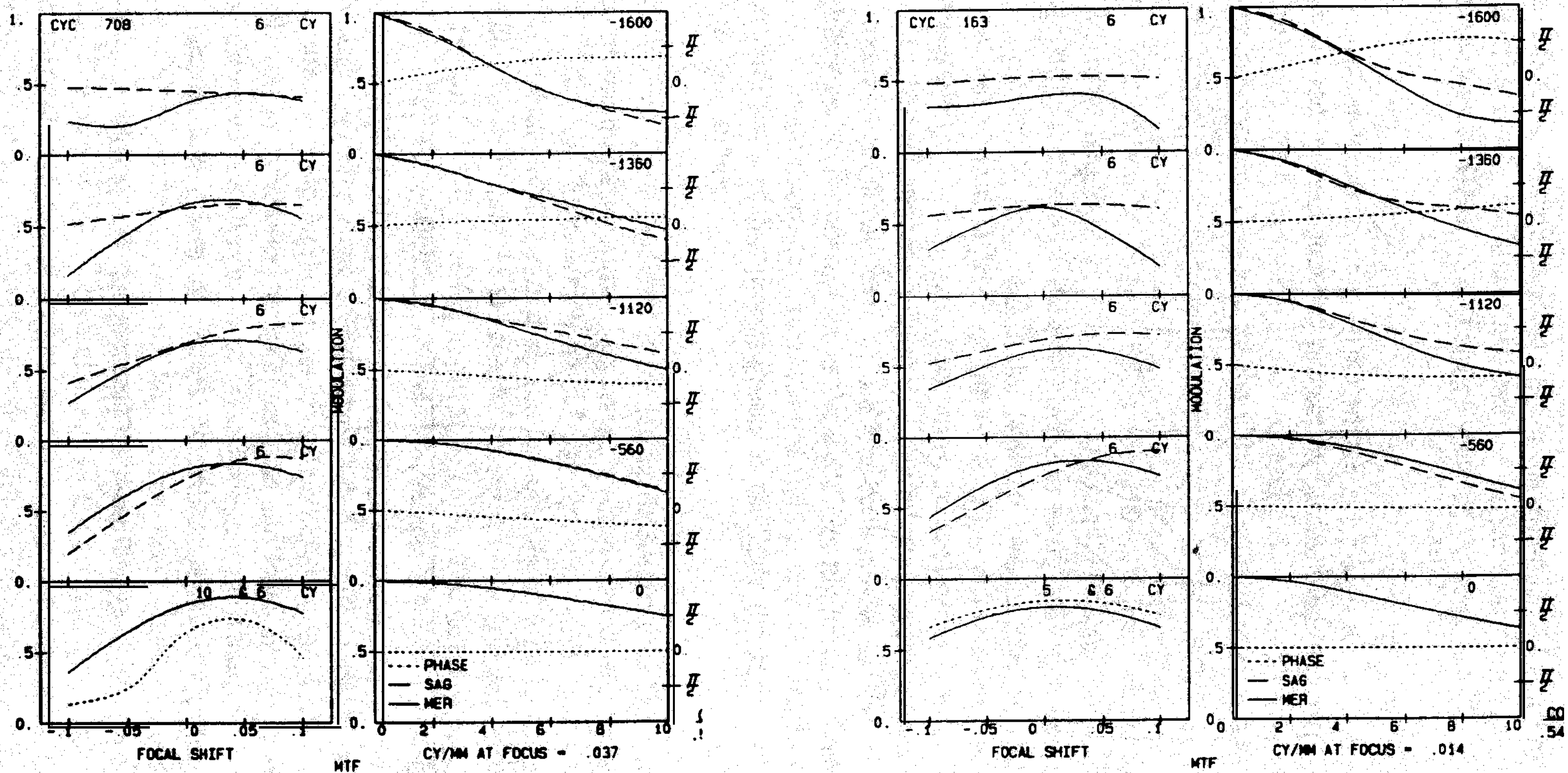


Figure 32 The HD-114 Lens.



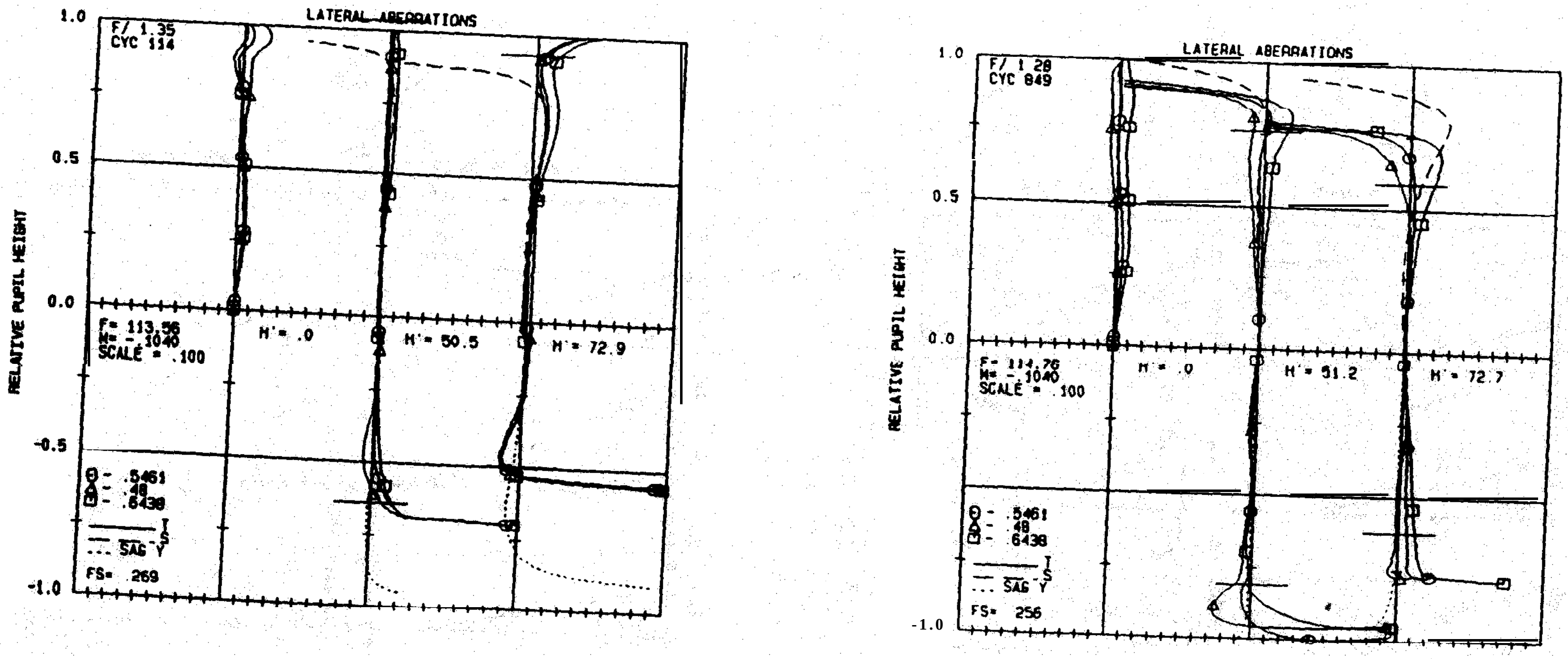
Figure, 34 The IBIS-1 16 Lens.



a) HD-8B

b) HD-114

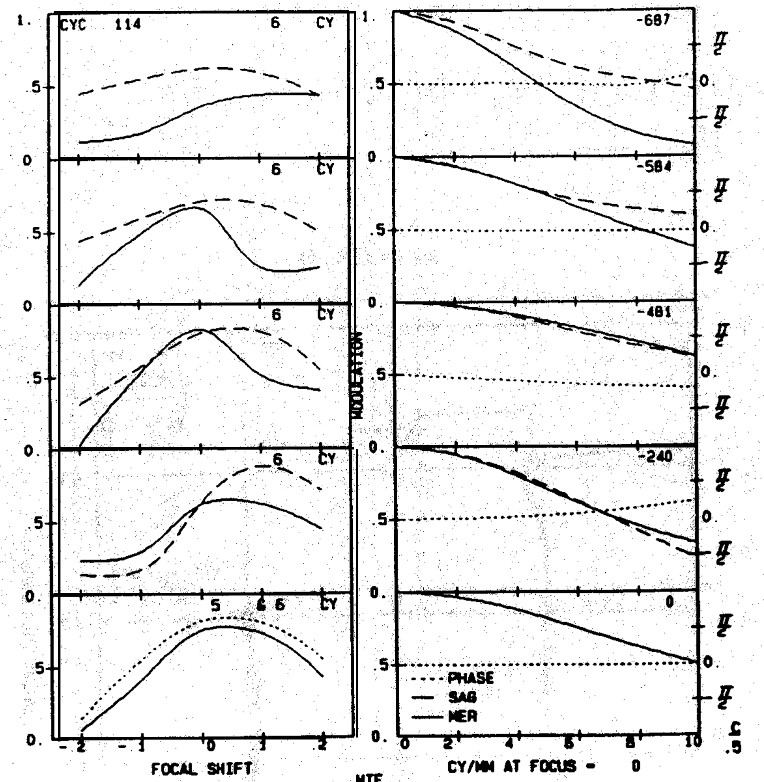
Figure 33 MTF curves



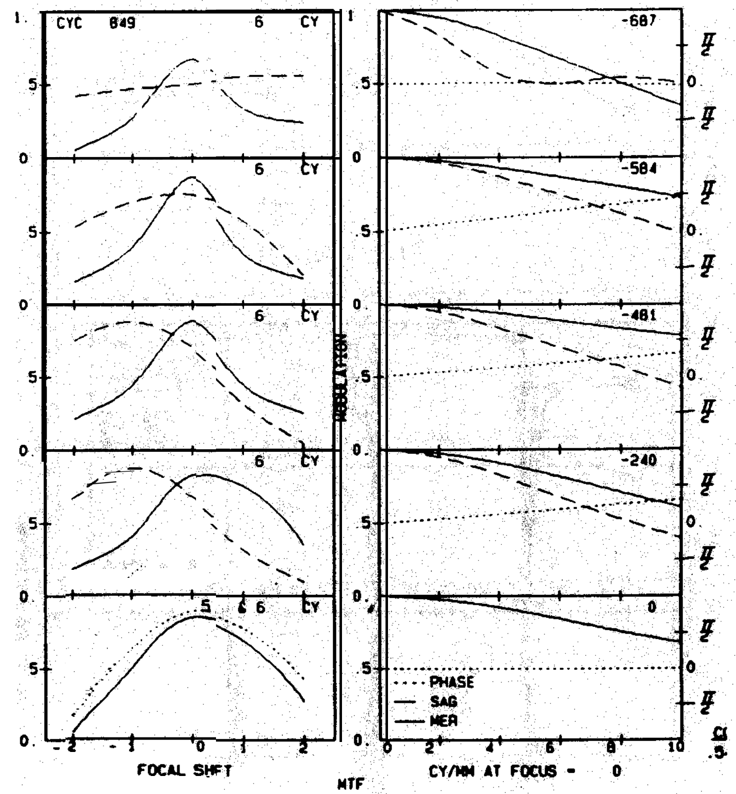
al HD- 114

b) IBIS. .6

Figure **35 Lateral** aberrat ion curves



a) HD-114



b) IBIS-116

Figure 36 MTF curves

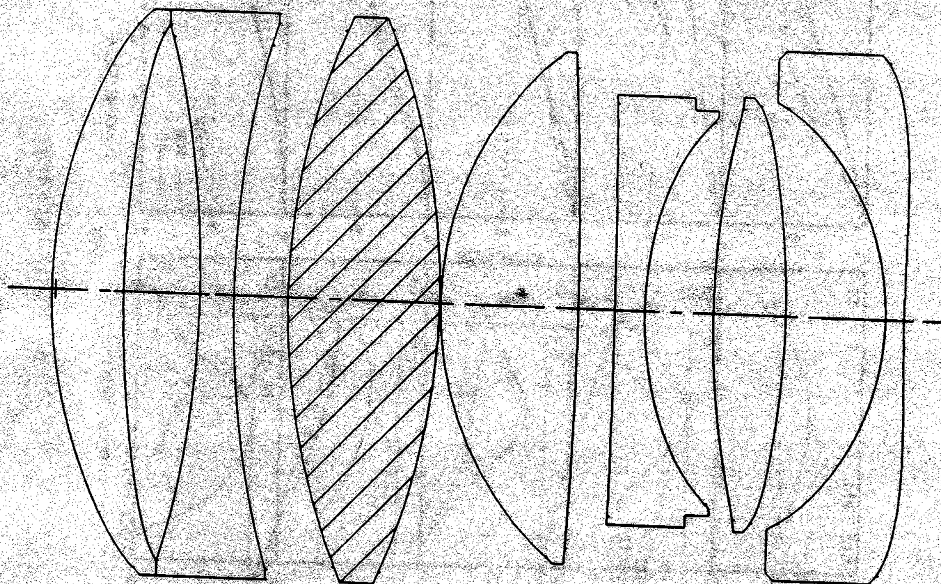
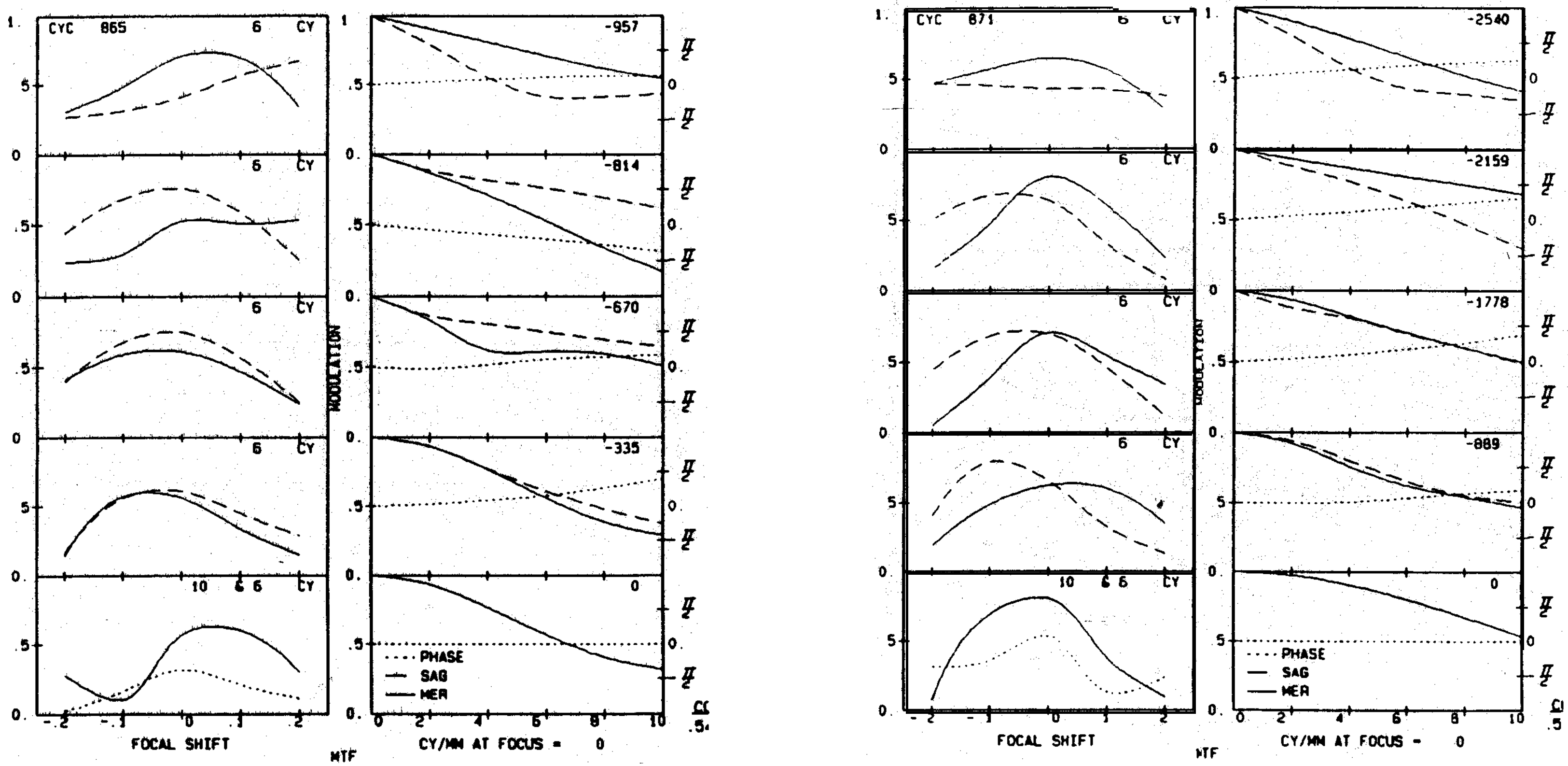


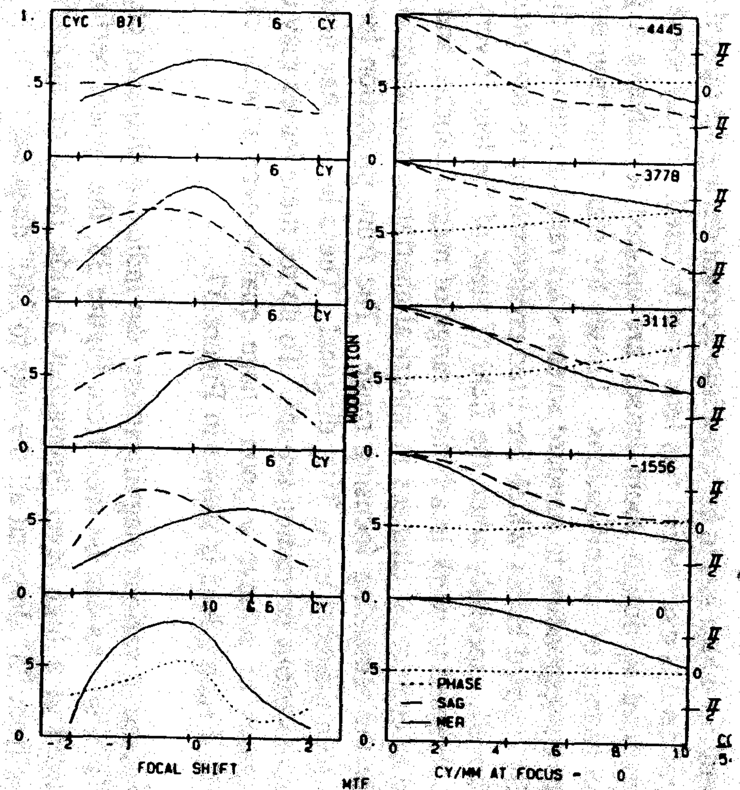
Figure 37 The Ibis-8 lens



a) 75" screen

b) 200" screen

Figure 38 MTF curves for IBIS-8



c) 350" screen

Figure 38 MTF curves for IBIS-8

The disadvantage of using this form of the lens is that it may take longer to prepare for production since the number of plastic elements is increased and the corresponding tooling is more involved. It is also important to know more precisely the temperature distribution inside the lens since the plastic elements' powers may be reasonably strong and the thermal focus drift may become severe if the individual powers are not balanced appropriately. The data in Figure 35 and Figure 36 shows the optical performance of the two lenses having the identical speed and the field of view. One of these lenses is HD-114 having three glass element in the power group and the other one is IBIS-l 16 having only one glass element. As can be seen, these lenses are nearly identical in image quality; however, the cost of IBIS lenses is appreciably lower than that of HD-114.

An important consideration which has to be taken into account during the optical design of a lens is the range of magnifications over which this lens must be used. Today some of the same methods and techniques used to design zoom lenses are applied to achieve a greater stability of image quality with change of magnifications. Lenses for rear projection sets must work at discreet magnifications corresponding to standard screen sizes ranging from 40" diagonal to 70" diagonal. The optically coupled lenses which are used predominately in rear projection applications tend to not focus well, especially when the field of view of the lens is very wide. In those instances the lens is designed to work in a limited range of magnifications, and one of the elements is then modified to correct for changes in spherical aberration and astigmatism to make the modified lens cover the remaining focusing range. The front projection lenses are often used from about 70" screen diagonal up to 350" diagonal. These lenses may need to be focused continuously to adapt to various projection set-ups. To do so, these lenses may use one or more variable internal spaces to achieve a good image quality over a wide range of magnifications. The example of such a lens is shown in Figure 37.

When this lens is focused at various magnifications, the indicated airspaces change in a predetermined non-linear fashion. As can be seen from Figure 38, the optical performance of this lens has been stabilized at a high level throughout a wide range of magnifications corresponding to screen sizes from 75" diagonal all the way to 350" diagonal.

As can be seen from the above, the process of designing a projection TV optics involves a multiplicity of tradeoffs. And, as expected, every manufacturer today has a wide variety of CRT projection lenses available to them.