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ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT

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Modern Display Technologies and Applications

NORTH ATLANTIC TREATY ORGANIZATION

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NORTH ATLANTIC TREATY ORGANIZATION

ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

AGARD Advisory Report No.169

MODERN DISPLAY TECHNOLOGIES AND APPLICATIONS

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This Advisory Report was prepared at the request
of the Avionics Panel of AGARD

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PREFACE

Visualization of aircraft situation and systems status has become increasingly important. It is generally agreed that in every phase of flight the pilot must be well informed; and thus supplied with each conceivably important piece of data pertaining to one of these phases. Obliging to such needs by simply increasing the number of dials or other displays in the cockpit increases the risk factor associated with the concurrent presentation of more and more raw data. Over the years AGARD has provided the forum where considerable attention was paid to improved instrumentation for the purposes of navigation, engine control, flight systems management and mission performance.

Recent AGARD publications devoted to this subject in particular are AGARD-AG-255: Advancement on Visualization Techniques, 1980, ed. W.M. Hollister; AGARD-LS-76: Electro-Optical Systems, 1975, eds. F.S. Stringer and J. Howard; AGARD-CP-167: Electronic Airborne Displays, 1975, ed. H. Leysieffer.

New technologies are now emerging which, together with the judicious application of computing power, will provide the pilot and other crew members with timely and well prepared information instead of just instantaneous raw data.

Electronically programmable display devices, capable of presenting alpha-numerics, vectors, graphs, flow diagrams and even gray-scale images become available. It is the purpose of this report to acquaint both the operational personnel as well as avionics systems scientists and designers with the back-ground, the capabilities and the state-of-the-art of these display technologies. Also, an estimation of the anticipated applications potential is included.

Working group 11 of the Avionics Panel of AGARD was charged with the task of collecting material on display technologies which are applicable to the aircraft, and more particularly, to the cockpit environment of the future. The following members were appointed: D. Bosman, Neth. (chairman); B. Gurman, US; W.M. Hollister, US; G. Hunt, UK; G. Meier, Ge; J.P. Michel, Fr.; D. Price, UK. The list of detailed addresses is given in Appendix 1 to this report.

The subject matter and the structure of this report were determined during six working sessions, each held in a location where specific information on one or more particular technologies could be obtained. The group feels indebted to their hosts: in several instances the body of knowledge so gained has added considerably to the ability of the group to appraise the potentialities of a technology. The contribution of the following individuals is gratefully acknowledged.

- In the USA: L.E. Tannas, Aerojet General Corp.; W.E. Bleha, Hughes Aircraft Company; C.E. Land, Sandia Laboratories; E. Schlam, Army Electronic Technical and Devices Laboratory; P. Seats, Thomas Electronics; K.T. Burnette, Bunker Ramo Corp.
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- In Germany, at FhG-IAF: G. Meier, L. Pickelmann, P. Schlotter; at VDO: W.H. Hucho, H. Baeger, H. Kister, W. Klein.

Some of the material compiled in this publication was borrowed from other reports and articles; where possible or relevant, the sources are referenced at the end of each (sub) chapter.

Finally, the group thanks all who shared the heavy burden of typing, drawing, etc.; their dedication has made possible the publication of this report.

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CHAPTER 1

INTRODUCTION TO THE REPORT

In aircraft, most variables and parameters are converted, processed and transmitted before being displayed. Such transformations must not distort the information, sought by the pilot, beyond the limits prescribed for each stage. Today the quality of the technical transformations is relatively easy to establish; not so, however, of the display function which brings about the final mapping of the technical data into cognizance. Typically, a display must meet two requirements: firstly it must be adequately seen under all conceivable circumstances and secondly, the data it displays must be in a form which matches to the pilot's inner representation of the state of the aircraft variables and parameters. The latter aspect is strongly represented in e.g. AGARD-AG-255 mentioned earlier, the physical and visual aspects dominate in this report.

The vast majority of indications are (as yet) in visual form, because the eye is better supported by the brain than all other sensors. Viewing conditions are difficult in the cockpit: the eye has to cope with the visual conditions of the natural world outside and the artificial environment inside. Every engineering effort must be made to satisfy the requirements of the visual channel, both in terms of avoiding undue viewing strains and in patterning the data to match the perceptive mechanism of the pilot.

The driving forces towards the implementation of electronic flat panel displays are many. Firstly, the present (electro)mechanical technology supported the development of a great variety of cockpit instruments. With the exception of only a few concepts (see below) each instrument was originally designed to realise only one function (one indicator for each measurand). The trend being progressively towards instrument flying, the instrument panel has now become cluttered with so many dedicated dials that it almost defeats its purpose of acting as the primary window on flight and mission performance.
Secondly, the signals driving the (electro)mechanical indicators are of very diverse formats; proper installation and maintenance requires personnel skilled in various disciplines. Similar considerations apply with respect to power requirements and heat dissipation.
Thirdly, there are the aspects of weight, accessability, reliability and cost (specialized spare parts and first line test equipment).
There is strong evidence that the electronic, programmable indicator eventually will outperform the now proven electromechanical designs, while simultaneously providing the solution to the problems of instrument panel clutter (programmable, integrated displays), of driving signals (compatible with digital data bus concepts, e.g. MIL.STD-1553B), and of power requirements, dissipation and weight; affording ease of replacement through commonality (highly similar, mass produced units).

In conventional aircraft instrumentation it has been shown that people have preferences for specific display formats (dial, scale, bars, numbers, text, mimic) depending on the form and the dynamic characteristics of the data. The one-to-one translation of the faces of electromechanical instruments onto a screen, in the form of a mêlée of electronic line drawings of dials and pointers, probably is a stage in the transition process towards electronic, programmable displays. Of course, the advantage of electronically realized dials is that scale factors are easily changed according to the situation - obviating the need for coarse - fine indicators which were required in some electro-mechanical instruments.
However, very much effort was spent in assessing the error frequency of reading the dials of mechanical primary flight instruments (1.1), and it is not unlikely that aviation authorities may ask for similar evidence in the case of electronic presentation.

The history of flight instruments (1.2) shows a steady and rather cautious development backed up by experience gathered from long use. The familiar mechanical device was long unrivalled, except for some very specific functions such as radar, malfunction indicators and the like. Many mechanical instruments support only one dedicated dial for each single variable; only during the last three decades some integrated instruments like the head up display (HUD) (1.3), the attitude director indicator (ADI), and multi-engine instruments became operational. In the HUD and the ADI the "integration" concerns the coincident indication of closely related, but different, measurands where, in a model, simultaneously their magnitudes and mutual relations are shown. This provides the pilot with more accessible information about the aircraft's attitude than an equivalent number of separate indicators would. In the multi-engine instrument the relations shown are of a simpler nature (comparison of spoolspeeds, EPR, EGT).

These types of instruments not only require less panel space, but also more closely match the pilot's mental representation of his task and enhance the quality of the operation. Further, many types of detailed data (different flight regimes, mission stage, malfunction alarms) are not simultaneously required. The scanning of many dials can be replaced by calling up according to need the appropiate data in a programmable display. Application of computers will aid in relieving perceptive strain by reducing the rate of presentation of generated data to match the rate required by the mental model of the task.

The understanding of human decision and control behaviour (mental representation or model, Fig. 1.1) has gradually increased, such that one may design other types of displays matched to specific tasks (1.4), (1.5), (1.6), (1.7).
Thereby it may be expected that the workload required to obtain taskbound information can be substantially reduced, i.e. by limiting the amounts and the rates of data obtained through scanning, which require both retention in short-term memory and mental processing.

From the ergonomic point of view there is thus room for improvement and, in that respect, the ability of easy electronic programming of opto-electronic devices is superior over electromechanical displays. The (re)programmability is also an important asset in fail-safe operation, since the pilot (or the safety-monitor system) may choose to override displayed data in favour of primary data wanted at a particular stage of the mission.

Of course, the many years of research spent on the visual and dynamic requirements of aircraft displays are being used to advantage in the design of opto-electronic displays, especially for those aspects which the mechanical and the opto-electronic technologies have in common. However, much additional research has been carried out and is still required, not only in the area of selection and structuring of data clusters to be programmed for specific tasks, but also for the determination of viewing characteristics of opto-electronic displays which are different from those of diffusely reflecting electromechanical dial faces (1.8), (1.9).

For instance, the viewing quality aspect. Apart from the familiar factors which determine legibility, like contrast, size, resolution and form of black/white and colored symbols (1.10), (1.11), (1.12), (1.13), detection and legibility can be impaired by phenomena like wash-out (1.13) or its counterpart display glow (1.14), flicker (1.11), high data density (1.15) and vibration induced illusions in scanning type displays (1.16).
For further literature on such subjects, see the list of literature to this chapter: 1.17 through 1.22.

Such human factors, which affect the applicability of the opto-electronic technologies for aircraft use, are given attention in chapters 2 and 4 from the point of view of the user. It must be emphasized, however, that the wealth of human factors data (ophthalmological, psycho-physical and purely psychological) now available is often not readily applicable to engineering problems. They provide norms for engineering results, seldom guiding rules for design.

Multi-disciplinary research aimed at obtaining such rules is now being conducted in several institutions but needs more time and support. The results of this research effort are validated through opinion polls involving a sufficient number of pilots.

In Chapter 3 the electro-optic and opto-electronic technologies are described. The familiar Cathode Ray Tube (CRT) is included because this technology is available and in acceptable form for installation in the cockpit. Of the flat panel technologies only the plasma displays are highly developed, others like LED, electro-chromic, liquid crystals and electro-luminescence are rapidly emerging. Still others are in very early stages of development (1.9). The attention given to each technology is about proportional to their maturity for aircraft indicator design.
To facilitate objective comparison, each (important) technology is given a separate section laid out in a standard format:
- brief historical survey,
- principle(s) of operation,
- physical characteristics (including construction),
- addressing, driving,
- system interface, other than driving requirements,
- viewing characteristics,
- state of development.

In Chapter 4 the required display characteristics for various applications are reviewed. The applications range from high-complexity, high accuracy displays such as vector-graphic HUD to message and discrete alphanumeric displays. This applications chapter is an introduction to Chapter 5 which attempts an assessment of modern display technologies for the applications reviewed in Chapter 4. As there are still many unknowns to be resolved in some of these technologies, the assessment is tentative and by no means complete; however, believed to be the first of its kind for aircraft applications, the Working Group expects it can be useful.

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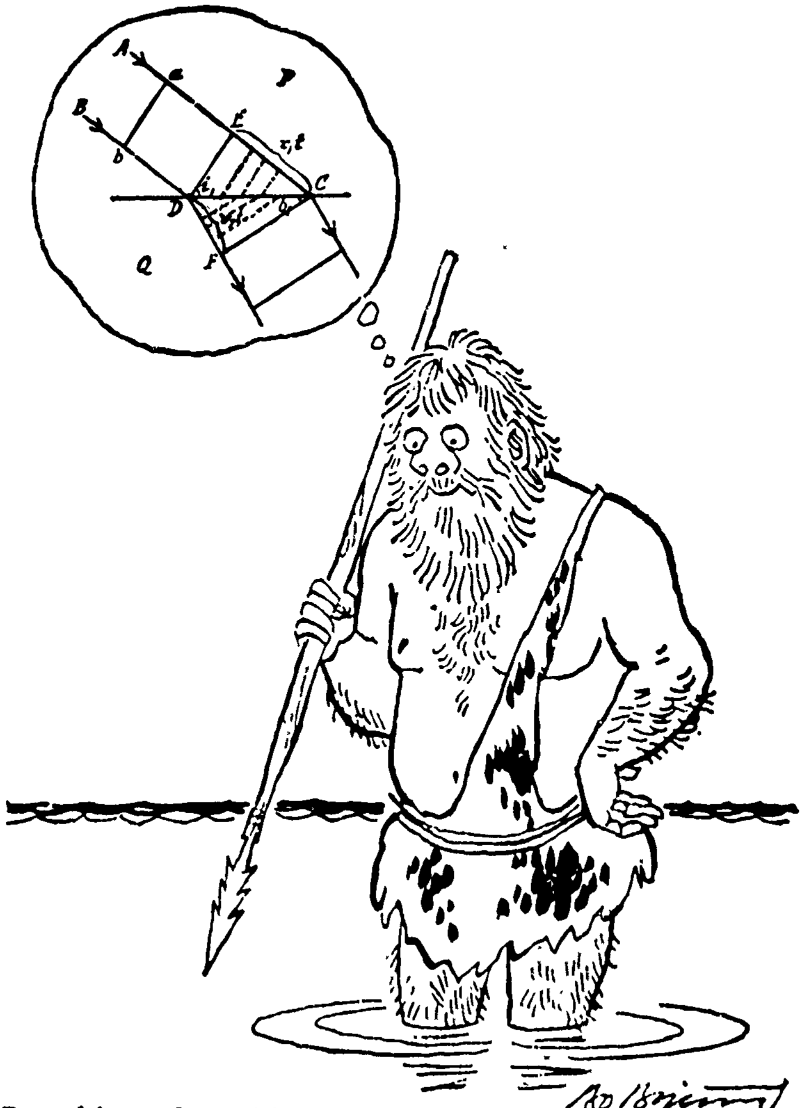

Forundring er begyndelsen til tænkning.

Fig. 1.1 "Mental Model"
Bo Bojesen in "Politiken".

CHAPTER 2

AN ENGINEERING VIEW ON VISION AND DISPLAYS

A total display system is a window, permitting the operator (pilot) to perceive the state and the dynamics of all the parameters which are relevant to his task.
The performance of the visual interface between machine and brain is determined by technical and ergonomic factors. Many of these are described in this chapter, in order to provide a basis for better interpretation of such data in assessing display performance specifications.

The main technical factors are:
- optical, including luminance contrast and color contrast of the display in its environment, the sharpness and steadiness of its image, and other technical qualities such as absence of distortions, spatial homogeneity of addressed and background areas/segments, independence of contrast of viewing angle, etc.
- image generation, from addressing techniques to quantization effects.

The main ergonomic factors, including the ophthalmic and psycho-physical factors but excluding the task-derived, are for the purpose of this report grouped into the following categories:
- viewing characteristics as a function of environment/surround conditions, including luminous efficiency and temporal response of the eye, visual acuity, contrast thresholds as a function of the eye's adaptation state, visual search data, sensitivity to flicker.
- legibility of displayed symbols.
- factors associated with the use of color. Although colorimetric data pertain to the domain of physics, the perception of color as used in e.g. a display is a human factor.

2.1 THE TECHNICAL FACTORS AFFECTING THE PERCEPTION OF DISPLAYED DATA

2.1.1 OPTICAL FACTORS

First, some definitions of the field of optics will be recalled.
The radiant energy Q_r of a light emitting display is only partly emitted in the form of luminous energy Q_v; a major fraction is spectrally located in the near and far infra-red regions, causing heat which must be dissipated along well defined and controlled channels. The associated IR emission can be troublesome; interference can occur with night vision systems on the aircraft and IR radiated from the cockpit adds to its detectability.
The radiant flux, or power P_r, is equal to the rate of flow of radiant energy. The distribution $P_r(\lambda)$ of power over the contributing components with wavelength λ is the power spectral distribution of P_r. In Fig. 2.1 the normalized spectral distributions for a 2000 K radiating black body, a green and a red light emitting diode (LED), and a P43 phosphor are depicted. The larger the area under the curve, the more overall energy is radiated.
If a photo-sensitive sensor is stimulated by P_r, its sensitivity being also dependent on the wavelength λ, its output will be the weighted sum of radiated power and sensitivity:

$$\int S(\lambda).P_r(\lambda).d\lambda$$

In the case of the eye/display system, and assuming that the non-luminous fraction emitted and/or reflected by the display is neither hazardous nor irritating, one is only concerned with the radiant power which stimulates the sensors in the human eye. The <u>luminous flux</u> F is equal to the experience of visual stimulation brought about by P_r.

The luminous efficacy function K_m $V(\lambda)$ of the human eye varies with the wavelength λ and with the intensity of stimulation, see Fig. 2.10. The sensation of light thus is weighted by K_m $V(\lambda)$:

$$F = \int F(\lambda)d\lambda \text{ or } F = K_m \int_{400}^{750} V(\lambda).P_r(\lambda)d\lambda.$$

The integration interval is in practice determined by the luminosity interval outside which $V(\lambda)$ is almost zero. The unit of luminous flux is lumen, K_m is lumen per Watt. Under photopic conditions, K_m is 673 lm W^{-1}, under scotopic conditions 1725 lm W^{-1} (see section 2.3.1).
In light emitting displays the fraction Q_v/Q_r usually is very small. For reflective type displays, the energy of (desired) reflected light (both diffuse and specular) can be much higher. This does not automatically mean that they have superior viewing characteristics, since Weber's law states that contrast perception is constant if the just noticeable difference (JND) of luminance ΔL between two adjacent surfaces is proportional to the absolute luminance of the duller surface.

2.1.1.1 luminous units.

To relate luminance, illumination and brightness to luminous flux the following is apropriate (2.1), (2.2).

- for a point source, the luminous intensity I (candle-power) is the luminous flux per unit solid angle $\frac{dF}{d\omega}$ (see Fig. 2.2.a) in lumen per steradian (lm sr^{-1}) or candela (cd);
- the illuminance E is equal to the luminous flux per unit area $\frac{dF}{dA}$ (incidence normal to the surface), expressed in lux (lx).
  Illuminance is a measure of the flux received by a given area;
- An illuminated, non-black surface will reflect some of the light incident upon it, partly specular, partly in a wide range of directions (diffuse). The surface thus resembles a self-luminous surface. The emitted luminous intensity per unit projected area is the luminance $L = \frac{dI}{dA \cos \phi}$ (see Fig. 2.2.b), its unit being cd m^{-2} (nit).
  Luminance measures the flux emitted in a given direction. A much used practical definition is: a uniform diffuser which emits a total flux of 1 lm cm^{-2} is said to have a luminance of 1 lambert (L, not a SI unit):
  $1 \text{ L} = \frac{1}{\pi}.10^4$ candela m^{-2}.
- The perceived luminance or brightness is determined by the retinal illumination. In Fig. 2.2.c the surface element dA_1 emits, in a direction with angle ϕ normal to its surface, a flux F with luminous intensity dI. The area A_2 of the pupil of the eye transmits the fraction dF of the flux F onto the retina, where the image dA_3 is formed of the emitting surface dA_1.
  Now:

$$dF = dI \frac{A_2}{r^2} = L\, dA_1 \cos \phi. \frac{A_2}{r^2}$$

  The area of the retinal image dA_3 is roughly equal to

$$dA_3 = dA_1 \cos \phi. \frac{\ell^2}{r^2} .$$

  wherein r: distance of the observed surface to some point in the eye lens and ℓ: separation between the retina and some (other, but close) point in the lens.
  Consequently the retinal illumination is determined by:

$$E_v = \frac{dF}{dA_3} = T_v \frac{L.A_2}{\ell^2} \text{ (}T_v\text{: transmission factor of the eye)}$$

and thus the brightness sensation is not dependent of the area A_1 of the surface observed, neither of the distance r, nor of the angle of inclination ϕ; however, it is linearly dependent of its luminance L provided the pupil area A_2 remains constant. However, the above does not apply to point sources (élement size near limit of visual resolution) such as Light Emitting Diodes (LED's), see 2.3.2. The unit of retinal illumination is the troland: $L.A_2$ (nits mm^2).

When diffusely emitting or reflecting surfaces are observed, the brightness often seems independent of the angle of inclination of the surface. This property is very useful in displays, as it affords a wide viewing angle. From the considerations about the retinal illumination it follows that the emitted luminous intensity per unit projected area, or luminance L, must remain constant, irrespective of the radiation directions. Since the definition of luminance is $L = \frac{dI}{dA \cos \phi}$, the luminous intensity I must follow a cosine law: Lambertian radiation (Fig. 2.2.b).
A luminous surface which exhibits this characteristic is called a uniformly diffusing surface.

There are many optical units in use, although the SI (Système International) units given here are preferred. In the British system:
- luminous flux is expressed in lumen,
- luminous intensity: candela,
- illuminance: 1 foot-candle (lm ft^{-2}) = 10.76 lux,
- luminance: candela per square foot (cd ft^{-2}). A uniform diffuser which emits a total flux of 1 lumen per square foot has luminance of 1 foot-lambert: (1 fL) = 3.43 cd m^{-2}.

To understand the conversion factor between the foot-lambert and cd m^{-2}, or between the lambert and the cd m^{-2}, one must realize that the uniform diffuser emits light in all directions, whereas the candela relates to only the solid angle of one steradian. It can be shown that the luminance L of a uniform diffuser which emits a flux of P lumen per square meter is: $L = \frac{P}{\pi}$. Thus the conversion factor between the foot-lambert and the candela per square meter is $(\frac{m}{foot})^2 . \frac{1}{\pi} = 3.43$.
Practical numbers for the luminance of e.g. suitably mounted cathode ray tubes (CRT's) are:
- office use, computer terminals: 50-200 cd m^{-2}.
- aircraft, HUD: green display line 5.10^3 cd m^{-2}, provided that there is adequate color contrast against the background (2.3).
- aircraft, HDD: 3.10^4 cd m^{-2} (2.3).

2.1.2 CONTRAST DEFINITIONS

To achieve such high luminances is a difficult engineering problem, solved at the cost of high power dissipation. The high luminance is, however, only required to contrast against high background luminance. It has been shown that people do not require very high levels of luminance contrast on the display face, so that the average power dissipation can be markedly decreased by controlling the light output of the display to match the adaptation state of the eye caused by the mean retinal illumination in the broad field of view, in order to keep contrast within a small acceptable range.
Filters can be used to reduce the effect of illumination falling directly on the display.

As already stated, the concept of contrast is a controversial notion. There is luminance contrast (achromatic or irrespective of color), color contrast (at equal luminance) and a combination of both (2.4). These concepts can be defined exactly and reproduced under laboratory conditions. For instance, luminance contrast threshold is measured when a small (e.g. 10 mm) symbol such as a disc, a ring with a square gap or a numeral with a (foreground) luminance L_f is just noticeable against a large, wide angle of view, background with luminance L_b when L_f/L_b or L_b/L_f exceeds a threshold value.

One may define e.g. the luminance contrast and modulation depth:

$$C_e = L_f/L_b, \quad C_v = | L_f - L_b | / L_b, \quad MD = (L_f - L_b) / (L_f + L_b).$$

C_e is the simpler definition and is used much in engineering.
Although C_e can be easily converted into C_v through $C_v = | C_e - 1 |$, C_v seems to be the logical choice when the eye is involved because the law of Weber-Fechner states that the perceived sensation is a logarithmic function of the stimulus (in other words, the just noticeable difference ΔL is proportional to L). The Modulation Depth (MD) is, however, more appropiate to the practice of flying where the luminance distribution is more complicated than under said laboratory conditions. A display is composed of a number of symbols and lines: when looking at one symbol, all the other foreground luminances merge into the background and contribute to L_f as modelled by the denominator of MD.
In psycho-physical measurements of contrast sensation MD is also used. The contrast sensitivity at threshold (50% detectability) equals its absolute reciprocal: $CS = |MD|^{-1}$.
Since under laboratory circumstances L_f, L_b and their respective areas are well controlled, CS is good scientific measure (see Figs. 2.12, 2.15, 2.16).

Table 2.1 below shows that the relationships of MD and C_e are logarithmically symmetric in the region of interest $.1 < C_e < 10$, C_v follows C_e closely for light-on-dark symbols but tracks MD for dark-on-light symbols.

Table 2.1

C_e	C_v	MD	CS
0.1	0.9	- 0.818	1.22
0.2	0.8	- 0.666	1.50
0.5	0.5	- 0.333	3.0
1	0	0	∞
2	1	+ 0.333	3.0
5	4	+ 0.666	1.50
10	9	+ 0.818	1.22

The light and color adaptation state of the eye is further influenced by surround luminance L_s, which is emitted or reflected from surfaces in parafoveal view. Also, the eye may be conditioned to outside luminance (from peripheral angles) when looking at the display: veiling luminance L_v.
Of course, to complicate matters, the logarithmic law (Weber-Fechner) is valid over only part of the range of luminance encountered in flying. Further, L_b and L_s can be composed of display (emissive) luminance in combination with (display) reflective luminance due to environmental light falling on both the display and the instrumentation panel.

Again, the reflections may also have a specular and a diffuse component, caussing the distribution of MD over the display face to be non-uniform. The detrimental effect of reflections, in particular specular, can be decreased by the use of light absorbing (black) background materials in the display and of specially designed display face materials and front covers. Transparent covers for active displays may be neutral having a low transmission factor (< 0.3), or color dependent, possessing a transmission factor which is very low throughout the spectral range except for display emission wavelengths. They enhance the contrast by decreasing the effect of environmental light on L_b because reflected external light which penetrates the cover travels twice through it and thus is attenuated twice, whereas pixels and display background emissions are attenuated only once, as depicted in Fig. 2.3. In some types of display the addressed pixels become visible through polarizers, or contrast enhancement is effected by a polarizing cover. The application of such displays must be carefully considered when the pilot or observer is likely to wear polarized glassess!

Because the viewing performance depends on contrast, and the contrast requirement depends on luminance level and resolution, it is recommended to control foreground luminance to keep MD within comfortable tolerance limits ($0.15 < MD < 0.8$). Simultaneously the L_b should be controlled to match surround luminance L_s, thereby attaining a uniformly distributed light level across the instrument panel so that adaptation delays are not incurred when switching attention. Also non-uniform brightness suggests to the observer that there are (intended) differences in attention value of displays: luminance and contrast of multiple displays must be approximately matched.

The question: what is the extend of the visual field which must be considered, has not been answered with any great precision. Blackwell (2.24), see section 2.3.3 and Fig. 2.15, has theoretically determined the contrast thresholds required to see a disc of variable size (area) under different background luminance conditions (adaptation state of the eye), but the applicability for edges other than contours around larger areas is questioned.

2.1.3 SPATIAL FREQUENCY RESPONSE OF OPTICAL SYSTEMS

An optical system will cause decrease of sharpness (blurring). This is true for a lens (system), however well focussed, and for an electronically addressed display. Blurring is evidenced by the fact that an infinitely small point source in the original image plane is reproduced as a dot of finite size (circular for the cathode ray tube or CRT, with an intensity gradient at the edges). The function which describes the blurring is called the Point Spread Function (PSF). Because blurring occurs for every point in the original image, one may describe the image in the presentation plane as being the result of convolving the original image with the PSF. If the PSF is invariant, irrespective of location of the pointsource and of time, the process is linear, time invariant.

One may obtain another description by taking the Fourier transform of the PSF: the result is the Modulation Transfer Function (MTF). It describes how well the frequency components of a point source (two-dimensional) or of a line (one-dimensional) are transmitted (reproduced) by the optical system or the display. The frequency components of the image are defined as the number or cycles per mm or, at a given viewing distance, cycles per degree of visual angle. The modulation depth (MD) at each spatial frequency is the dependent variable, see Fig. 2.4.a, which depicts the MTF's associated with a soft and a hard spot. In the case of the display it is assumed here that the reproduced image is continuous (not sampled either horizontally or vertically) and that a sufficient number of gray scales is available such that the MD may also be considered continuous. Gray scales are defined, analoguous to photography, as densities which differ by factors of $2^{\frac{1}{2}}$.

The MTF of an optical system, including the eye, can be determined by its response to sinusoidally modulated gratings with linearly varied MD. The MD where the grating is just (not) noticeable is measured for each spatial frequency; see section 2.3.1 for its effect on perceived contrast and spatial resolution of the eye. In general, the larger the area under the MTF, especially at the high frequency end, the more details can be distinguished in the image. Also, by increasing the contrast for high spatial frequencies (image processing), one may compensate for blur.

Above it was assumed that the PSF is invariant and, by implication, also the MTF is invariant. However, they depend on the adaptation state of the eye, thus e.g. on L_b, L_s and L_v, but also on the location within the field of view, etcetera.

2.1.4 SPATIAL FREQUENCIES, FRAME RATE AND VIDEO BANDWIDTH

The video bandwidth of a matrix or line scan (CRT) display is proportional to the frame repetition rate and the total (average) number of picture elements (pixels) or written length of all traces on the display face during one frame. For the familiar TV format, each frame consists of a number of lines, 625 in Europe, 525 in the US. The writing speed in both systems causes the beam of the CRT to traverse the width of the screen and return in 64 microsecs.

In Europe the frame repetition rate is 25 Hz, in the US: 30 Hz.
Such low frame rates cause problems with flicker perception, see 2.3.3, so that each frame is split up into two half frames or fields, displaced by one line with respect to each other (interlaced), such that perceived frame flicker is 50 Hz and 60 Hz respectively. This is alright for TV pictures, but the displacement causes jittery pictures for high contrast horizontal lines, e.g. in small size (5x7, 7x9) alpha-numeric characters, resulting in the "twinkle" effect.

For a display located at a viewing distance of 0.7 m (28"), and operated at a max. spatial frequency of e.g. 40 cycles per visual degree where the eye's response, at given luminance, field size, etc., requires an MD = 1 to just perceive the (sinusoidal) grating (2.3.1), the angle one such cycle subtends equals 0.3 mm on the display face. Assuming that the visible part of the face is 100 mm, one can distinguish about 300 cycles or 600 points on one horizontal line. If the beam traverses the visible part of a CRT in 50 microsec. then the video bandwidth extends from (almost) zero up to 6 MHz. Depending on its light intensity distribution, a spot size of 0.15 mm or less is required, irrespective of its location on the display face.

At such writing speeds and spot sizes, and in worst case (bright day-light) conditions, the resulting (average!) luminance of a CRT raster scan display is too low for aircraft use unless precautions are taken. Therefore, many aircraft CRT displays are used in the stroke writing mode wherein the beam does not write a full raster, but only the vectors required during each frame. Consequently, since face area utilization in this mode is only a small fraction (<< 10%), the total written length of the traces per field is smaller and thus the video bandwidth. However, to obtain sharp angles between vectors the CRT deflection current amplifiers must be able to supply high currents during short intervals, which is equivalent to strong high frequency video components. These components are not frame rate dependent, so that this rate can be increased to improve the luminance of the trace and thereby to obtain a higher contrast in worst case conditions. The problems of attainable luminance are aggravated with hybrid use of the CRT, where gray-level images and alpha-numeric symbols must be superimposed and remain indepedently legible. Further, vibration will cause blur which is similar to contrast degradation. Experience with present monochromatics shows that with collimated displays, such raster scan displays are feasible (2.3). Present HUD developments have shown that wash-out does not occur and that the eye adapts quickly, while lateral vibration has not been a problem in collimated presentations.

2.2 SAMPLING AND ADDRESSING

2.2.1 THE CATHODE RAY TUBE

In the TV rasterscan format the video information is, within the horizontal display width, continuous. The video signal which modulates the electron beam writes an image line in the phosphor: the visible result being the convolution of the modulating signal with the spot produced by the electron beam. The display MTF shown in Fig. 2.4.a can be regarded as representative for the horizontal CRT (line) presentation (2.5).

In the vertical direction of the rasterscan format, and in both directions of matrix addressed displays, the image is sampled. The resolution at which the display operates depends on the distance between lines or between individual points (picture elements or pixels, sometimes called pels; the latter abbreviation is also valid for the French "points élémentaires"). Insufficient resolution impairs the legibility of symbols, e.g. alpha-numerics (2.6), (2.7), (2.8).
In a matrix display the minimum distance is one pixel pitch, under the condition that the image is spatially "locked" to the grid of the matrix. When that is not the case, i.e. the images vibrate with respect to the grid, individual points of the image will subsequently address adjoining points of the display grid - resulting in unsteady appearance and twinkle effect. This is particularly so when the subtense of the pixel distance is larger than 0.1 milli-radian (0.4 minute of arc) which is the resolving power of the eye for high contrast, sharp edges.

In a CRT rasterscan format, and with digital character or image generation, the CRT beam is switched in tens of nanoseconds; generating sharp edges which are more or less comparable to the edges of the pixels of many flat panel displays. See Fig. 2.4.a. This produces distortion when diffuse spatial luminance transitions are required. One way to decrease this effect is to add dither (a random motion) to, or to defocus the beam of the CRT, purposely blurring the sharp edges. A more elegant solution was pioneered by e.g. Craggs and Mitchell (2.9) wherein use is made of the spatial electron density distribution of the electron beam, in order to simulate the diffuse transitions in slanted lines, as shown in Fig. 2.5. The full line intensity is preceded and followed by a slowly increasing and decreasing intensity which has the appearance of modulating the line width because of the electron density distribution of the beam, thus producing the illusion of less distortion. Of course, the rate of increase/decrease must be computed to match the slant angle, being zero for vertical lines.

In CRT shadow mask color displays yet another source of discretization limits the resolution still further: the three color dots per line decrease video bandwidth per color by a factor of 3. Although individual spot size per color remains comparable, the amount (3.1.6.1) of addressable spots of equal color is smaller. Again high resolution is obtainable by proper combinations, i.e. operation at gray levels.

Thus the video luminance bandwidth of a color CRT is larger than the video chrominance bandwidth. This fact is not consistent with e.g. the use of color as a redundant coding attribute which must assist in rapid recognition of predominantly shape-coded symbols. However, in practice this limitation is not severe, since the resolution of the human eye for colors is also lower than for black and white; at the lower subtense limits, color symbols require about 50% larger symbols than black and white for equal error rate performance (2.7), (2.8).
For vector scan type presentations quite different considerations prevail (3.1.5).

2.2.2 THE MATRIX DISPLAY

The quantization effected in matrix displays is comparable to hard-switched digitally generated TV formats without diffuse spatial luminance transitions. This need not be objectionable, provided the small character fonts (e.g. 5 x 7, 7 x 9)

- are designed to match the cartesian nature of the matrix, i.e. do not require high resolution in other directions than either horizontal or vertical (no rotation!),
- are not required to travel across the display in other directions than the matrix coordinates.

Of course these two limitations must be seen in relation to the pixel size at the viewing distance, the total number of pixels on the display area, and to the contrast sensitivity Fig. 2.4.b, (1.18), (2.24) of the human eye. Present electronic matrix displays still have technological teething troubles and problems with drive electronics which at the moment pose upper limits (for reliable operation) to the total amount of pixels of about 50.000 to 250.000. This amount is sufficient for alpha-numerics and certain pictorial displays (2.10), (Fig. 2.6), but must be considered too low for quality graphics. The state-of-the-art is growing rapidly and the next 5 years will show a marked improvement towards more addressable pixels per display area, as already is the case with plasma display panels.

However, this latter objective is at variance with another development of matrix-addressed displays: the desire to provide memory in order to obtain 100% duty cycle, which will be discussed further below.

2.2.3 LINE AT A TIME ADDRESSING

Addressing matrix displays is accomplished by using two orthogonal sets of parallel conductors (rows and columns) to provide e.g. a current or electric field to display elements located at the intersections. One difficulty is obvious: when two display elements located at x_i, y_j and x_k, y_l are desired then, with simultaneously powered lines i and k, and columns j and l, two "parasitic" elements x_k, y_j and x_i, y_l also appear. This phenomenon can be avoided by line-at-a-time addressing. So, in a 200 x 300 element display, 300 columns are normally selected concurrently, while the 200 lines are "scanned", one at a time, see Fig. 2.7.a. With N lines, the scanning frequency must be higher than N times the critical flicker fusion (CFF) frequency (section 2.3.3) at the experienced ambient illumination of the display.
Obviously, all the display elements located along non-selected lines and selected columns are "half-selected"; equally so the display elements located at the selected lines and the non-selected columns. To illustrate the effect of this addressing method on e.g. LCD displays, the maximum ratio for rms ON voltage over rms OFF voltage for addressed and non-selected pixels (2.11) is shown (2.11) to be:

$$R_{max} = \left[\frac{N^{\frac{1}{2}} + 1}{N^{\frac{1}{2}} - 1} \right]^{\frac{1}{2}}$$

for a matrix with N line electrodes. This ratio converges asymptotically to 1 for large N. For instance, R = 1.073 for N = 200: in that case the voltage interval between ON and OFF state of a cell is only .073 times the driving voltage.
Thus, unless the activation characteristic of the display material is highly non-linear, all the non-selected display elements will glow weakly also, presenting a visual noise pattern (in general non-uniform) as background glow. An improvement over the half-selection scheme is shown in Fig. 2.7.b: the third selection scheme wherein only one-third of the full drive potential is applied to non-selected display elements. Other schemes, aimed at obtaining higher on-off ratio and/or simpler addressing matrices, are developed.

However, the parasitic background glow is not the only penalty involved with poor thresholds and line-at-a-time addressing: tolerance difficulties arise, with their

connected reliability problems.
Some materials, e.g. liquid crystals, also exhibit viewing angle limitations (see section 3.3) as function of the drive-threshold potential. Every effort is therefore being made to produce suitable non-linearities - either in the display material itself or through addition of one non-linear element such as a diode, a varistor or a transistor in series with each (!) display element (2.12), (1.17), as shown in Fig. 2.8.a. The latter technique is known as "active" matrix displays because it involves gain producing electronic components.

2.2.4 OTHER ADDRESSING SCHEMES

In high pixel-count displays the difficulties experienced with addressing are found on the one hand in the complexity of wiring, decoding and drive electronics, sometimes aggravated by the occurrence of high (charge) currents (with accompanying EMI); on the other hand the degradation of vision characteristics like lower frame rates (flicker) and increased viewing angle dependence (LCD's).

Active matrices have the advantage that the thresholding is shifted to the electronics (by e.g. a thin film transistor matrix, where each transistor is located near the driven pixel); with such arrangements it becomes possible to divorce the power requirements of each display element (which is heavy in the case of light emitting technology) from the decoding electronics. Moreover, the very important attribute of memory for each pixel becomes feasible because power drain is low in the addressing side of the matrix due to the gain of the electronics. A small capacitor for each matrix node (see Fig. 2.8.b) can provide sufficient charge to keep the display element in the "on" state for the duration of the frame. Thereby the duty cycle ("on" to "off" ratio) will rise to almost 100% resulting in a much higher light output or light modulating efficiency. Simultaneously the problems of CFF and vibration induced distortions are much alleviated.

In the case of LCD, the relaxation of the requirement of full addressability has led (2.13) to an ingenious matrix addressing scheme which is both flicker free and affords the maximum viewing angle because the ratio between "on" and "off" pixel voltage is high. The penalty is the fact that only one pixel in each column may be addressed. This restricts its application to oscilloscope and analogue pointer displays.

The method makes use of the correlation properties of pseudorandom binary sequence (prbs) waveforms. Each line electrode of the display is driven by a different prbs. These have the property that the voltage difference between any two of them is pure a.c. and has a constant RMS value (about 70% of the logic "1" voltage level) irrespective of which two are chosen: Fig. 2.9.b. If the i^{th} line ($i = 1, 2 3 \ldots\ldots$) has a prbs: V_i, applied and the j^{th} column als has V_i applied, the result is that the i^{th} pixel in the j^{th} column will experience zero voltage difference continuously (Fig. 2.9.a) and are "off".
All of the remaining pixels in this column will experience alternating voltage differences having a high RMS value and will turn fully "on". Since the prbs waveforms have only two voltage levels (e.g. 0 V and 15 V) the electrodes may be driven directly from the output of CMOS logic circuits without the need for the special multilevel drive circuits required by multiplexing techniques.

The display background noise is spatio-temporal random, unlike in line-at-a-time schemes where the whole display background is periodically modulated and thus provokes a considerably intenser flicker experience. In this scheme the refresh rate of the image is equal to the repetition rate of the prbs which is, of course, inversely proportional to the number of lines (resolution) and therefore 2 to 3 orders of magnitude lower than the clock frequency of the prbs.
The application of the display is limited to data with low dynamic requirements.

2.3 HUMAN FACTORS AFFECTING DISPLAY DESIGN AND USE

2.3.1 RESOLUTION, MTF

When speaking of eye characteristics (2.14), (2.15) it is important to state the conditions of both eye adaptation and of the field of view. The dark adapted eye (scotopic vision) is, in terms of resolution and sensitivity for luminance and color, different from the eye adapted to bright sunlight (photopic vision): see Figs. 2.10 and 2.11.

The higher luminous sensitivity is physically located in the rods which sense brightness only. Rods are (almost) absent in the central part of the foveal area, where cones (color sensors) are dominant. The sensor density is highest in the foveal area (about 10^5 per mm^2) decreasing towards the peripheral region. Under photopic conditions, in the central foveal region, the resolution and the color perception are much better than in the parafoveal and peripheral view. Eye characteristics normally are quoted under such viewing conditions and therefore represent the optimally attainable perception. In a cockpit when a single instrument is fixated, most of the remaining instrument panel area falls out-side this superior viewing angle: the cone of sharp viewing is about 2^o, which means that a round area of 1 cm radius is seen sharp at the viewing distance of 0.7 m. With conventional instruments, this area encompasses hardly more than the business end of a pointer together with the immediately surrounding part of the dial.

The visual acuity as function of the viewing direction and as function of luminance (foveal view) are depicted in Figs. 2.12.a and 2.12.b, (1.13), (1.22), (1.23). These values are upper limits; dynamic visual acuity is lower; visual acuity also depends on eye accommodation and on color. The optimal focus range of a healthy young eye is from infinity to about 0.1 m but this range deteriorates rapidly with age. The focal accommodation time ranges from 1 to 8 secs. Color perception has lower resolution than luminance perception (about 3 x) (1.13, pp 135-141) (2.8). Also the color abberation of the eye optical system results in smaller resolving power. Thus the subtense under which a color display is seen must be larger than for black and white (under optimal viewing conditions).

Edges, such as are found in display images, require contrast to be adequately perceived. The eye can be regarded as an optical system. Although very non-linear, one may linearize its response under normalized conditions and thus apply linear notions such as Fourier transform (2.16), (2.17). The modulation transfer function (MTF) for achromatic light at moderate luminance levels, measured under threshold conditions, is shown in Fig. 2.4.b. For harmonic gratings it reaches a maximum contrast sensitivity for spatial frequencies of 3 to 4 cycles per (retinal) degree (cpd). This peak is less pronounced for bar gratings. The MTF appears a bit color dependent at the high frequency end (2.18). The power spectral density of the transform of a contrast edge which subtends an angle of ϕ degrees is largely concentrated in the range of zero to ϕ^{-1} cycles per degree. In terms of display resolution the experience of the sharpness of the edge is different, depending whether ϕ^{-1} is lower than 3 cycles per degree or much higher. In the first case, the higher spatial frequencies are amplified relative to the lower ones, with the result that the perception of the sharpness of the edge is enhanced; whereas in the second all higher components are attuated relative to the lower; thus contributing less to the experienced sharpness. See Fig. 2.13, which shows the mollified perception (c) of the sharp line (a) through attenuation of high frequency components of its spectrum (b). Under high brightness conditions the MTF shifts to the right, meaning higher resolving power. Also for bar patterns (instead of sinusoidal gratings) a better contrast sensitivity is experienced.

The perception of contrast disappears for retinal frequencies higher than about 60 cpd under all conditions, including supra-threshold (ST). Supra-threshold contrast perception is measured e.g. in contrast matching experiments, comparing perceived contrast of a sample with that of a reference. Recently (2.19) it was experimentally shown that, in the range of 1-12 cpd and under ST conditions, the perceived contrast $C_{ST}(f)$ is proportional to the difference between the absolute contrast C_A of the sample object and the threshold contrast $C_{TH}(f)$ obtained at the same frequency and luminance level. This implies that, at least in the observed frequency range, the perceived contrast $C_{ST}(f)$ is less frequency dependent than the threshold contrast $C_{TH}(f)$: more detail is recognizable under ST conditions. At sufficient luminance and contrast levels one can resolve a displacement of two bars (vernier acuity, Fig. 2.12.b) of only 0.4 minute of arc. Translating this to display resolution: for a direct view display with sharp edge transitions and seen at 0.7 m distance, the vernier acuity amounts to relative displacements of $\frac{0.4}{57.60}$ 0.7 m = 0.08 mm. Consequently, the limit of resolution is 1200 pixels on a line across a 100 mm wide display, which is twice the resolution calculated for moderate light levels (section 2.1.4). Of course, insufficient resolution invites a decrease in viewing distance (by leaning forward).

2.3.2 SCANNING

For reading the indicated value, a redirection, refocus, fixation and response time are involved, together from between 0.4 to about 2 sec. (1.12), (1.22), (2.20), (2.21). The time required is smaller when the display/pointer position has not changed since the previous reading, thus can be remembered and quickly recognized. However, doing so requires that one can aim the direction of view with an a priori accuracy of about 2^o; a value which is confirmed by experiment.

Normal pointing angles of the eye without additional head movement are about + 25^o (up), - 35^o (down) and $\pm$ 15^o sideways (2.22), (2.23). In the area bounded by these limits the optimum viewing characteristics (foveal) can be utilized for primary display instruments. For concurrent indications (fixed head) the parafoveal area, subtended by 12^o extra, can be added; at 0.7 m viewing distance leading to the viewing area of Fig. 2.14. Indicators which should often be scanned, must lie in such an area centered around the major direction of view, while indicators which must be seen irrespective of head movement may be advantageously helmet mounted.

Indicators which of necessity must be mounted outside this viewing area ($\pm$ 30^o from operator's line of sight) should be scanned less frequently; thus, for comparable attention value with fixed head orientation, they must be larger and must not rely on intricate symbol forms and color, because in peripheral vision the resolution of the eye and its color sensitivity are much degraded.

2.3.3 SPATIAL AND TEMPORAL LUMINANCE VARIATIONS

The eye is sensitive to spatial luminance variations (threshold sizes as function of display contrast) and to temporal luminance variations (blinking, flicker, twinkle sensation) as function of modulation depth. For round, homogeneously illuminated targets Blackwell (2.24) has researched the relation between contrast thresholds vs visual angle (foreground) as a function of eye adaptation. The latter is dependent on display and surround luminance in the cockpit and also on outside viewing conditions (1.13, pp 259-276). Fig. 2.15 shows graphs of these contrast thresholds which depict "worst case" luminance requirements for 50% probability of detection of single dots (pixels). Others also have determined, under varying conditions, the minimum contrast required to resolve two dots or lines. Carel (2.25), (2.2) has adapted Blackwell's results into guidance rules for calculation of display design, useful for performance/cost analysis on a relative basis which may show where there is room for improvement and/or the (in)flexibility of constraints. Based on this work, one can model (2.26) the relation, recommended for comfortable (supra threshold) viewing and short reaction times, between required foreground luminance L_f and background luminance L_b, valid for pixel sizes Δx (in minutes of arc) in the range $1 < \Delta x < 5$:

$$\frac{L_f-L_b}{L_b} = (2.7+15.L_b{}^{-0.67}).(\Delta x_2)^{-2}$$

the factor 2.7 being dominant in the high background luminance range 10^4 - 1 cd m^{-2}, the factor $15.L_b{}^{-0.67}$ in the low luminance range 1 - 10^{-5} cd m^{-2}; see Table I.

Table 1

L_b[cd m^{-2}]	$(L_f-L_b)/L_b$	$2.7+15L^{-0.67}$	$L_f(\Delta x_2=1)$ cd[m^{-2}]
$(10.000)^{-1}$	450	7200	0.7
$(1.000)^{-1}$	120	1500	1.5
$(100)^{-1}$	20	330	3.3
10^{-1}	3.2	73	7.4
1	0.9	18	19
10	0.42	5.9	70
100	0.22	3.4	440
1000	0.18	2.9	3.900
10.000	0.16	2.7	37.000

The expression describes the desired supra threshold contrast factor, and determines the modulation of the driving voltage u of the pixel. Assume a driving characteristic $L = C_1.u^{\gamma}$, then $\Delta L/L = \gamma.\Delta u/u$. Let the luminance of the driven pixel be $L_f = L_p + L_b$ so that $L_p = L_f-L_b$; of the non-addressed pixel L_b— the emitted light flux is just about zero, u_b its associated bias voltage. Thus $L_p = \Delta L$ and the relation becomes

$$\frac{\Delta L}{L} = \frac{L_p}{L_b} = \gamma\frac{\Delta u}{u} = (2.7+15L_b{}^{-0.67})(\Delta x_2)^{-2}$$

For a pixel size of 1 minute of arc, over the luminance range of photopic view ($L > 3$ cd m^{-2}), the driving voltage Δu can be proportional to u_b provided the display $\gamma = 2.7$ and the background driving voltage u_b is proportional to L_b.

In the foregoing nothing has been said about the use of non-uniform diffusers. However, some reflecting surfaces do emit a fraction in the form of specular reflection; e.g. some Liquid Crystal Displays, also the L_b of a CRT is partly specular. Light emitting diodes (LED) and certain contrast enhancing covers are non-lambertian radiators. It should be possible to design the total geometry to make use of the non-lambertian distribution by pointing "lobes" toward the user of the display. Otherwise, the consequence is that the contrast becomes dependent upon the angle of inclination of the display surface with the line of sight, which restricts the viewing angle and forces the design towards a worst case rating.

The perception of temporal luminance variations depends among others on the flicker frequency, the luminance, the size (retinal angle) of the flickering field and on the viewing angle (2.27), (2.28), (1.11), (1.12). In Fig. 2.16 the critical fusion frequency is shown for which the sensation of luminance variation is just not noticeable at lower modulation depth. For the area under the curve, the modulation is perceived. This curve depends on the average luminance level, and is measured under photopic conditions in the central (foveal) region, for a disc size compatible with the maximum contrast sensitivity (Fig. 2.4.b). For smaller flickering fields the required modulation depths are higher (1.11), (2.27).

The flicker sensitivity of the eye is higher in peripheral view directions, even though the receptor density is lower. However, few simple, conclusive, engineering data exist about avoiding the detrimental effect of flicker sensitivity in peripheral view, with stimulation from many directions and different solid angles, as experienced in front of large area instrument panels like in a cockpit using mixed technologies.

2.3.4 LEGIBILITY

Legibility is a complex notion, operationally defined as composed of the elements:

- symbol reading error
- word reading error
- average fixation time
- allowable thresholds of such operational inputs as: display illumination, surround luminance, structural characteristics of (and ratio between) diffuse and specular reflections, viewing distance and angle, eye accommodation and (various sources of) blur, (momentary) luminance adaptation level of the eye.
  There are some very complex interactions between the input factors and legibility, see Fig. 2.17. Experience obtained through research for the book printing profession taught that such functions can experimentally be optimized (2.7), (2.8), (1.12), (1.13), using notions such as
- font: basic geometry and "style" of a set of (alpha-numeric) characters;
- stroke width-to-height ratio or relative active area: the proportion of a symbol which actually emits or reflects light (important in dot-matrix representation);
- symbol width-to-height ratio;
- symbol spacing: important to the perception of word-Gestalt;
- size of the alphabet: number of characters with maximally different features, including sub- and superscripts;
- size of the wordset and the "feature distance" between words.

The symbol height determines the subtense under which the symbol is seen at a given viewing distance. Legibility is different for given symbol subtense under varying conditions of luminance, contrast, blur, resolution and technology. For instance, for raster scan and dot-matrix displays, symbol subtense must be larger for coarsely quantized symbols (6 lines/symbol → 36 minutes of arc, 12 lines/symbol → 15 minutes of arc) (2.8), (1.12).
Symbol quantization is another important parameter. For the restricted range of symbols such as the decimal numbers, the seven bar display is satisfactory. For the range of alpha-numeric symbols the lower limit for symbol quantization is the 5 x 7 matrix. This yields just acceptable error performance under favourable reading conditions and at maximum visual resolution (see section 2.3.1).

Also involved is the parameter in Fig. 2.17 which is not objectively measurable, namely "font". Several designs made specifically for computer generated characters have been proposed (2.7), (2.29). The measurement of their effectiveness is part of human factors methodology. For matrix displays with an orthogonal grid supporting non-rotatable alphanumerics the modified "Huddleston" font (Fig. 4.5) presently appears optimal for the 5 x 7 character block; the "Lincoln Mitre" font for 7 x 9 and larger. However, this optimum with respect to other fonts fortunately is rather flat. When the symbols must "withstand" rotation such as in an ADI, the size of the character block must be at least 14 x 11 pixels to avoid excessive distortions of the symbols as they remain locked to the grid. This effect is less severe in the case of stroke-written symbols (only the end points of the strokes written by the vector generator are locked to the grid), because a higher effective resolution is obtained. This technique is, however, limited to basically analogue applications such as possible in CRT displays.

Correct symbol spacing aids the recognizability of words. Most of the data available on this topic were collected for non-elctronic display media. Values ranging from 25-200 percent of symbol width are acceptable, with 50% a good middle value (2.8).

Percent active area is important for displays with a uniform luminance technology, e.g. reflective type displays, electro-luminescence (EL). The larger the area the more light output per dot, which benefits the legibility (2.30). However, at constant luminous flux (e.g. LED's) the luminance varies inversely proportional with area, so that contrast increases with smaller active area. Provided the resolution requirements of the eye are met, for LED type dot-matrix displays small active area per dot or pixel is proven to be the more economical way to increase legibility (2.31). An added physical advantage is that the power efficiency of the LED improves at subresolution size.

The variation of contrast as a function of viewing angle (LCD, LED mechanisms) is highly dependent on the type of technology. Usually such data are available. For viewing angles smaller than 30^0 the foreshortening of symbol width or height does not impair the legibility (2.8).

2.3.5 ENVIRONMENTAL EFFECTS ON LEGIBILITY

When a direct view display is vibrated with respect to the eyes, three effects are possible which may cause deterioration of the legibility.

Firstly, the commonly experienced phenomenon in continuously (not intermittently) energized displays is, that the contrast of edges perpendicular to the sense of vibration become blurred. The reading error depends on the frequency of vibration; at low frequencies the legibility remains acceptable for the larger sizes of symbols (1.16), (2.32).

Secondly, the effect associated with the periodically refreshed (flickering) type of display, with a frame rate higher than the fusion frequency and with moderate to long persistence contrast or luminance (e.g. LCD, CRT). For large excursions in retinal angle (such as rolling head of the pilot) multiple complete images are seen superimposed.

Thirdly, in matrix displays with short persistence pixels (LED, DC plasma and EL) which are e.g. horizontally scanned and strongly vibrated vertically, the scanned lines appear to break up to the extent that text and numbers become incomprehensible.

Collimated displays are much more tolerant to vibration (2.33).

Condensation, dust etc. may cause blur, but the display legibility must remain "sufficient". Blur degrades resolution and causes the MTF (Fig. 2.4.a) to fall off more at the higher spatial frequencies. Consequently, the symbol identification must not rely on high resolution. Assuming that symbol subtense is large enough to permit good legibility, actual practice has shown that 10 pixels/symbol height (14 for TV) (2.8), (2.29), are desirable (16 to 20 with requirement for subscript and superscript).

2.4 COLOR IN DISPLAYS

2.4.1 THE VALUE OF COLOR IN DISPLAYS

The use of color in display technology (1.13), (1.19), (2.34) is mainly for coding purposes, to improve perception by adding color contrast to luminance contrast. As such, the notion of just noticeable differences (JND) is more important than the notions used to describe the color sensation proper. However, one cannot very well describe the mechanisms involved without properly defining the psychological concepts of perceived color (2.14), (2.35).

Achromatic color perception is defined as one not possessing a hue. Hue is the attribute of a color perception denoted by red, yellow, green and so on: the degree of saturation being the "difference" between the perceived color and the achromatic color perception most resembling it. Brightness sensation is caused by the perceived luminance of a luminous source, independent of its color. Chromaticness of a color is determined by the attributes hue and saturation.

Perceived color cannot be measured objectively. For instance, the perceived color depends on the eye's adaptation state which, among others, is influenced by the dominant color preceding the color stimulus and by the prevailing color of the surround. Even under ideal conditions a specific color sensation Q can be induced by radiant fluxes with different spectral distributions (metameric colors). With the eye adapted to other than ideal conditions, these metameric colors can be perceived with differing hues and saturation. Similar effects are possible with isomeric (identical spectral distributions) colors. An example of simultaneous color contrast induction is the perceived color (hue) of e.g. a green line which extends into both brown and blue backgrounds such as may be realized in an electronic ADI: in order to maintain the same hue along the line the objective color (as measured with a spectra radiometer) must be changed at the intersection with the two backgrounds. Another example is that certain colors change hue with luminance and with ambient (surround) illumination (2.14), (2.36); conversely the detection thresholds at low light levels are also color dependent, but in a different way. Such dependences can be measured and tabulated objectively in a statistical sense, but may vary considerably from person to person.

The color vision properties of the eye are different for very dim, low light level scenery (scotopic vision) as compared to the other extreme, high level (surround, veiling) luminance. Most experiments with eye response to color were carried out at comfortable luminances; however, especially in the last two decades much attention is given to the extrema. At very low light levels, the general threshold (luminance) and the specific threshold (hue) coincide for red, are different for other hues: colorless interval (2.37). Red is the most saturated hue, greenish-yellow (520-580 nm) the least (1.19), (2.37).

For a 2^{0} field, under photopic conditions, the JND are given in Fig. 2.18 where it is shown that e.g. the blue- green and the yellow JND thresholds are lower than the red JND threshold (2.38). This determines the tolerances in the driving signals of a CRT display, and in the homogeneity of color selective filters, etc. Experiments with very high surround luminances (2.20), (2.39) have indicated that hue wash-out occurs easily for yellow, followed by green and blue, and is the least for red.

Under varying illumination, degree of saturation is a poor code. In addition, it was found (2.40) that very saturated colors, used in low to normal surround luminance conditions, induce fatigue and must be avoided. Because brightness coding also affords low resolution (1.12, p 76), (1.13, p 112) color coding mainly must be limited to selections and combinations of hues; form coding remaining the most versatile (size, shape, orientation, alpha-numerics). The use of hue, for a 100% identifiability under worst case conditions, is also restricted to e.g. 4 by (low level) threshold and (high level) wash-out effects, by accommodation difficulties of the average healthy eye and by the existence of certain color anomalies (2.14, pp 154-168). The increase (through color coding) of the set of 100% identifiable symbols in practice seems limited to a factor of about 2, but in many cases the search and reaction times are much shorter and a better mental picture is obtained (1.12-13), (1.15), (1.18-19), (1.22-23). Presently the value of color is insufficiently researched, although there is some tradition in colored mechanical displays (ADI, map displays). There appears to be a strong user preference for color, as evidenced by developments for Airbus and 767; but one cannot make predictions on the cost effectiveness in terms of coding quality and perception efficiency.

2.4.2 COLOR CHARACTERISTICS OF DISPLAYS

The results of numerous color coding experiments are not always comparable nor directly applicable. Some were obtained in trials with colored reflecting surfaces, others with colored light projected onto a diffusely reflecting surface, others with light emitting symbols. However, they make use of the same psycho-physical concepts (1.20), (2.35) which are objectively measurable. In the following these concepts and their interrelations are briefly introduced and defined where applicable to the field of displays.

Monochromatic color: an electro-magnetic wave $\vec{Q}(\lambda)$, its radiated energy located at wavelength λ and confined to a small band $\Delta\lambda$ around λ. The luminosity interval (p. 2.2) is bounded by $400 < \lambda < 750$ in nm. The color of any luminous flux $\vec{Q}$ can be matched by the additive mixture of three suitable monochromatic base colors, $\vec{R}$, $\vec{G}$ and $\vec{B}$: its representation in three dimensional color space given by (Fig. 2.19)

$$\vec{Q} = R.\vec{R} + G.\vec{G} + B.\vec{B}.$$

The equality is obtained by an experimental color and luminance matching operation. $\vec{R}$, $\vec{G}$ and $\vec{B}$ are the spectral primary colors; customarily chosen so that equal amounts produce an achromatic color sensation (white, equal energy spectrum). The wavelengths of $\vec{R}$, $\vec{G}$ and $\vec{B}$ have been standardized in 1931 by the Commission Internationale de l'Eclairage (CIE, ICI): their spectral locations are: $\vec{R}$ at 700 nm (red), $\vec{G}$ at 546.1 nm (green) and $\vec{B}$ at 435.8 nm (blue). The scalars R, G and B are the tristimulus values of the color $\vec{Q}$ in the system $\vec{R}$, $\vec{G}$, $\vec{B}$; their sum being the total luminous flux (in lumen if $|\vec{R}| = |\vec{G}| = |\vec{B}| =$ 1 lumen), their ratios representative of the perceived color. For instance: the tristimulus values of a color $\vec{Q}$ are R, G and B when the color and luminance of $\vec{Q}$ cannot be distinguished from the color and luminance of the additive mixture of R lumen $\vec{R}$, G lumen $\vec{G}$ and B lumen $\vec{B}$. Chromaticity is the point Q located at the intersection of the vector $\vec{Q}$ with the unit plane determined by $R + G + B = 1$ (the chromaticity diagram) in three dimensional color space). The chromaticity coordinates of Q are
$r = \frac{R}{R + G + B}$, $g = \frac{G}{R + B + G}$, $b = \frac{B}{R + B + G}$ with $r + b + g = 1$ independent of the luminous flux of $\vec{Q}$.

Most colors are not monochromatic, but their luminous fluxes F(Q) have power spectral density distributions $P(\lambda)d\lambda$ (Fig. 2.1). The resulting color $\vec{Q}$ is considered as the additive mixture of monochromatic colors $\vec{Q}(\lambda)d\lambda$ with tristimulus values $R(\lambda)d\lambda$, $G(\lambda)d\lambda$ and $B(\lambda)d\lambda$. Thus the color $\vec{Q} = \int \vec{Q}(\lambda)d\lambda$ has the tristimulus values $R = \int R(\lambda)d\lambda$, $G = \int G(\lambda)d\lambda$ and $B = \int B(\lambda)d\lambda$. The radiant power contribution of $Q(\lambda)d\lambda$ is $P(\lambda)d\lambda$; its chromaticity coordinates are $r(\lambda)$, $g(\lambda)$, $b(\lambda)$ obtained analoguous to r, g, b of $\vec{Q}$. Consequently $R = \int P(\lambda).r(\lambda)d\lambda$, $G = \int P(\lambda).g(\lambda)d\lambda$ and $B = \int P(\lambda).b(\lambda)d\lambda$. With this description, the color sensation induced by electromagnetic radiation of known spectral distribution can be predicted. In Fig. 2.20 the functions $R(\lambda)$, $G(\lambda)$ and $B(\lambda)$, depending on the wavelength λ_Q of $\vec{Q}$, are depicted for spectrally pure colors $\vec{Q}$ with luminous flux of 1 lumen ($|\vec{Q}| = 1$). The fact that $R(\lambda)$ and $G(\lambda)$ are partly negative means that matching is obtained by adding R lumen $\vec{R}$ and/or G lumen $\vec{G}$ to the source of $\vec{Q}$ instead. It follows that with these chosen base vectors not every spectral color can be obtained by an additive mixture, because negative light does not exist.

However, the requirement of negative power for a range of colors is inconvenient for colorimetry: the CIE adopted in 1931 a transformation of the trichromatic system based on $\vec{R}$, $\vec{G}$ and $\vec{B}$ to one based on new primaries $\vec{X}$, $\vec{Y}$, $\vec{Z}$ which are non-real - i.e. they cannot be realized by physical luminous sources and so remain outside the region of actual color vectors in three dimensional color space. The cromaticity coordinates are x, y, z analogous to r, g and b, and since these are dependent $(x + y + z = 1)$, the chromaticity of all real colors can be represented in an x, y diagram where all colors have equal luminance. The coordinates x and y determine hue and saturation, see Fig. 2.21. The locus of all spectrally pure (fully saturated) colors remains within the first quadrant. The straight line at the bottom, connecting blue and red is the purple line which borders non-spectral colors. See also Fig. 3.1.5.

A straight line connecting any two points P, R within the triangle determines the hue and saturation of the color Q obtained by the additive mixture of light sources with the chromaticity coordinates of the endpoints P and R. The equal energy stimulus E is located at $(\frac{1}{3}, \frac{1}{3})$ and represents an achromatic color (white, grey). A standard CIE white source C lies close to E. Within the color triangle, the relative distance $\frac{QC}{SC}$ between any point Q to the achromatic point represents the degree of saturation. The intersection S with the spectral locus of the line, connecting the chromaticity point Q of a color with that of C, determines the wavelength of the dominant color of Q. Its intersection T with the spectral locus in the opposite direction determines the complementary color. Color measurements are covered in e.g. 2.35.

Experiments have shown that the just noticeable differences (JND) in chromaticness are in the x, y diagram given by ellipses which differ greatly in size, depending on their position. Suggestions were made, therefore, to transform this diagram such that the JND ellipses would become approximately equal. This UCS (for Uniform Chromaticity Scale) diagram (Fig. 2.22), with the coordinates u, v was adopted by the CIE in 1960. In this figure the colors obtainable with a shadow mask color CRT (triangle RGB) are depicted. The chromaticity diagram is regularly refined (e.g. the 1976, CIE-UCS system in which the "ellipses" have a more circular shape). The UCS diagram is now commonly used in the specifications of color displays and in experiments concerning the effectiveness of color in displays.

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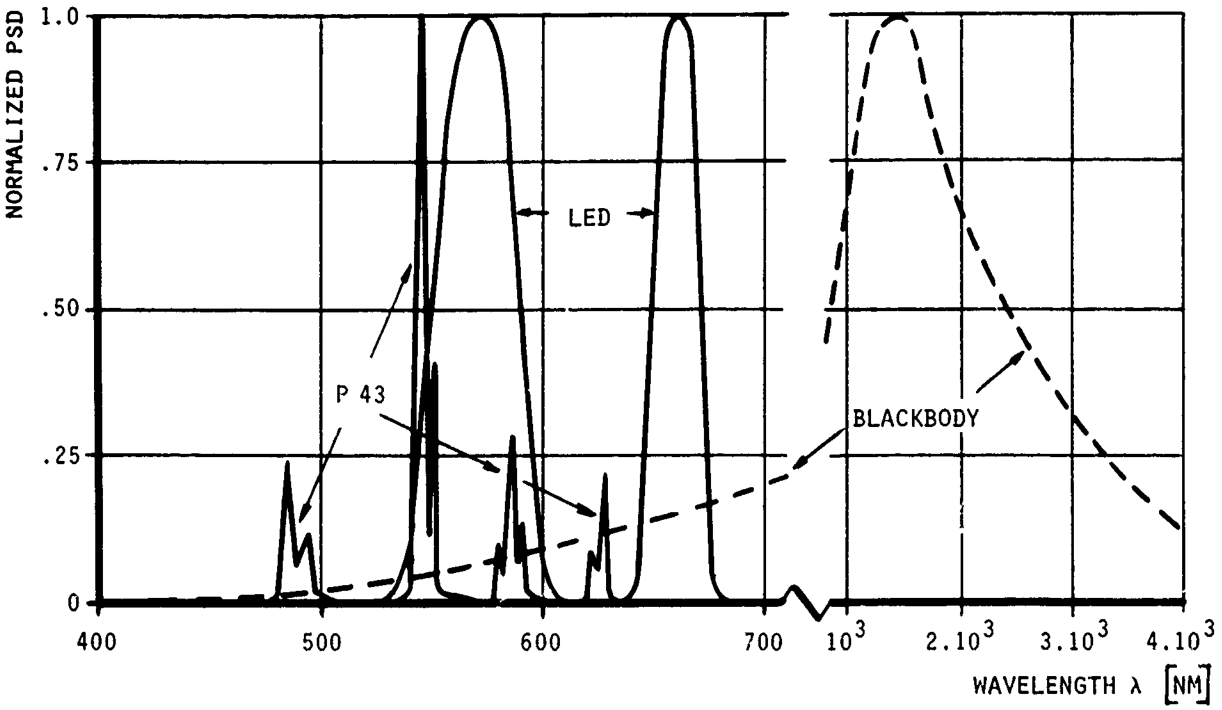


Fig.2.1 Power spectral densities (PSD) of three types of radiators

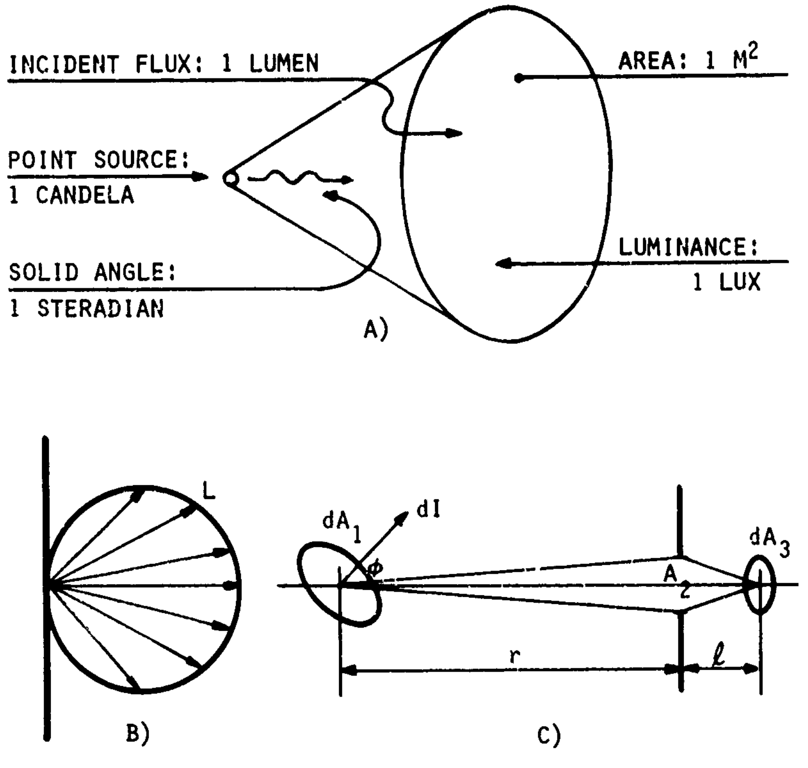


Fig.2.2 Illustrations to the definitions of section 2.1.1.1

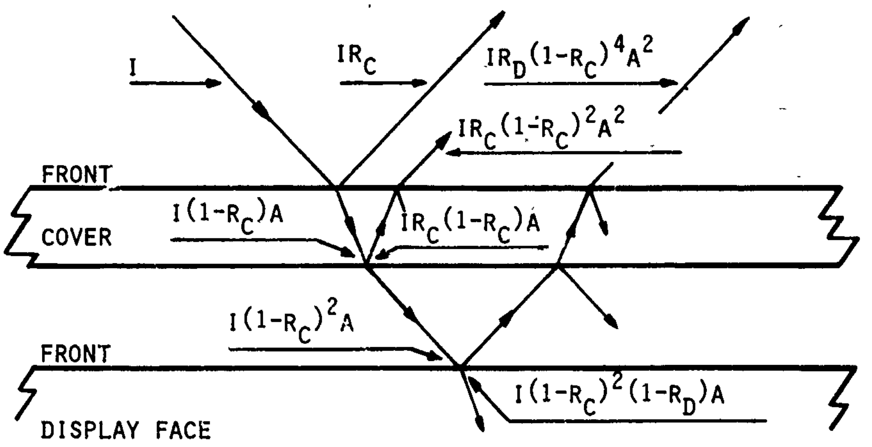


Fig.2.3 Transmission and reflection in contrast enhancing cover.
R_c, R_0: reflection coefficient, A: attenuation coefficient

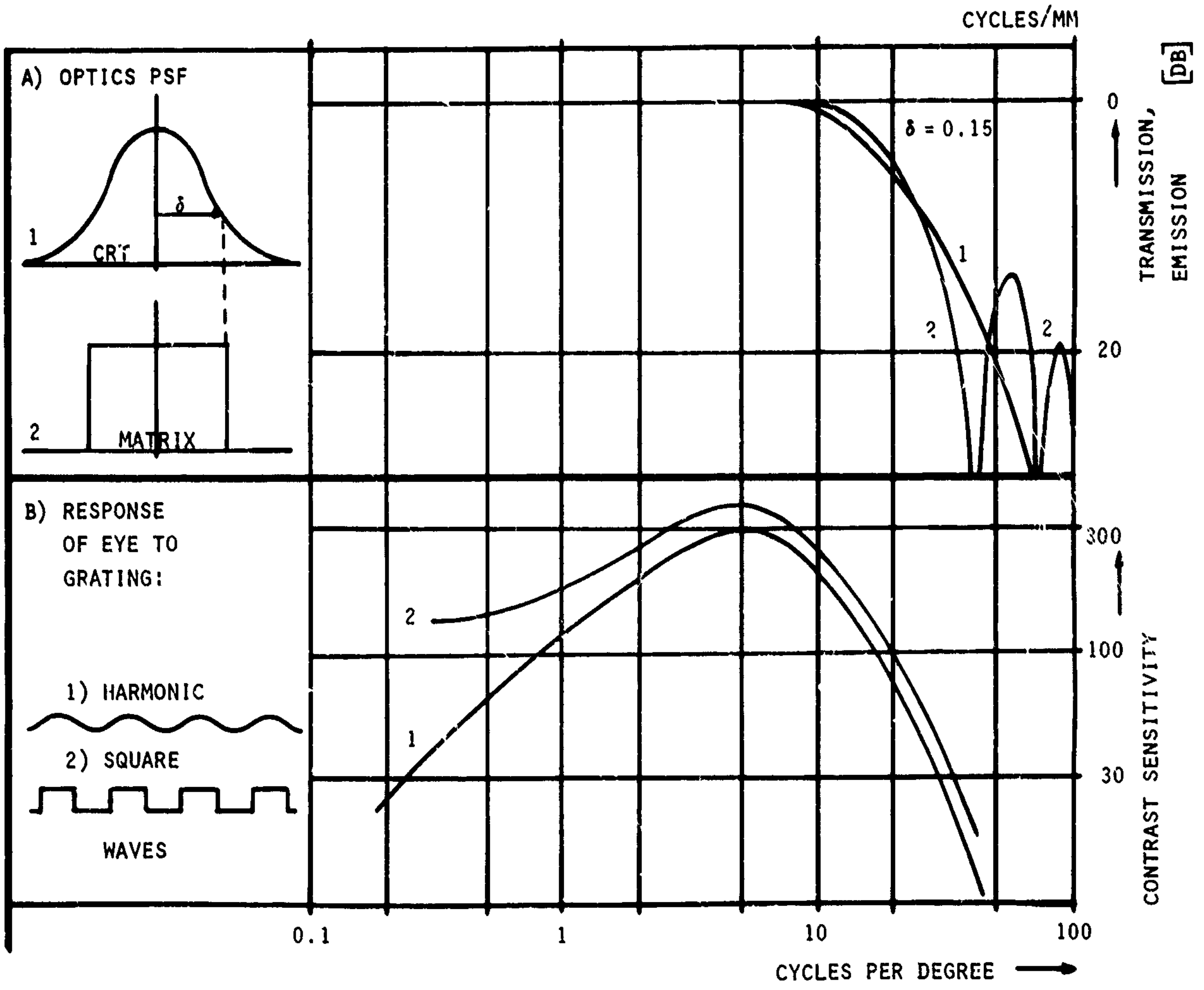


Fig.2.4 (a) CRT spot and matrix pixel luminance density distributions with their Fourier transforms
(b) Modulation Transfer Function of the average photopic human eye

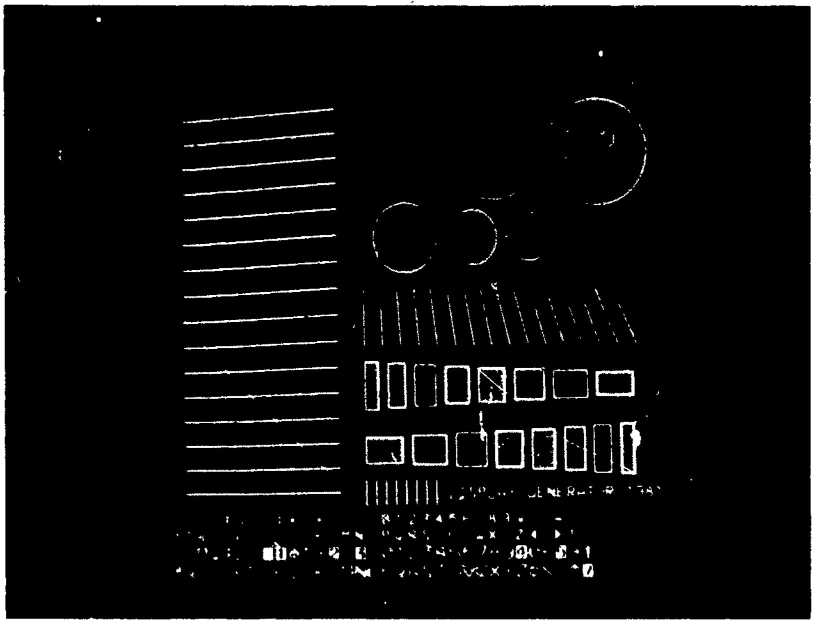


Fig.2.5 Improved quality raster scan display

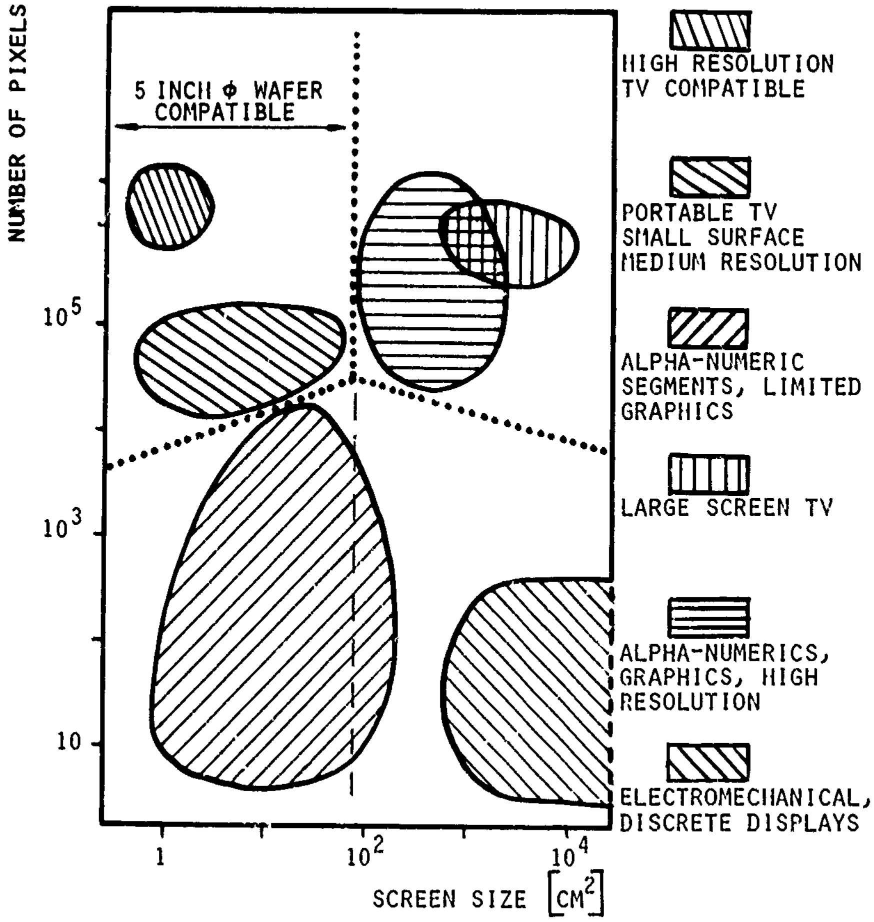
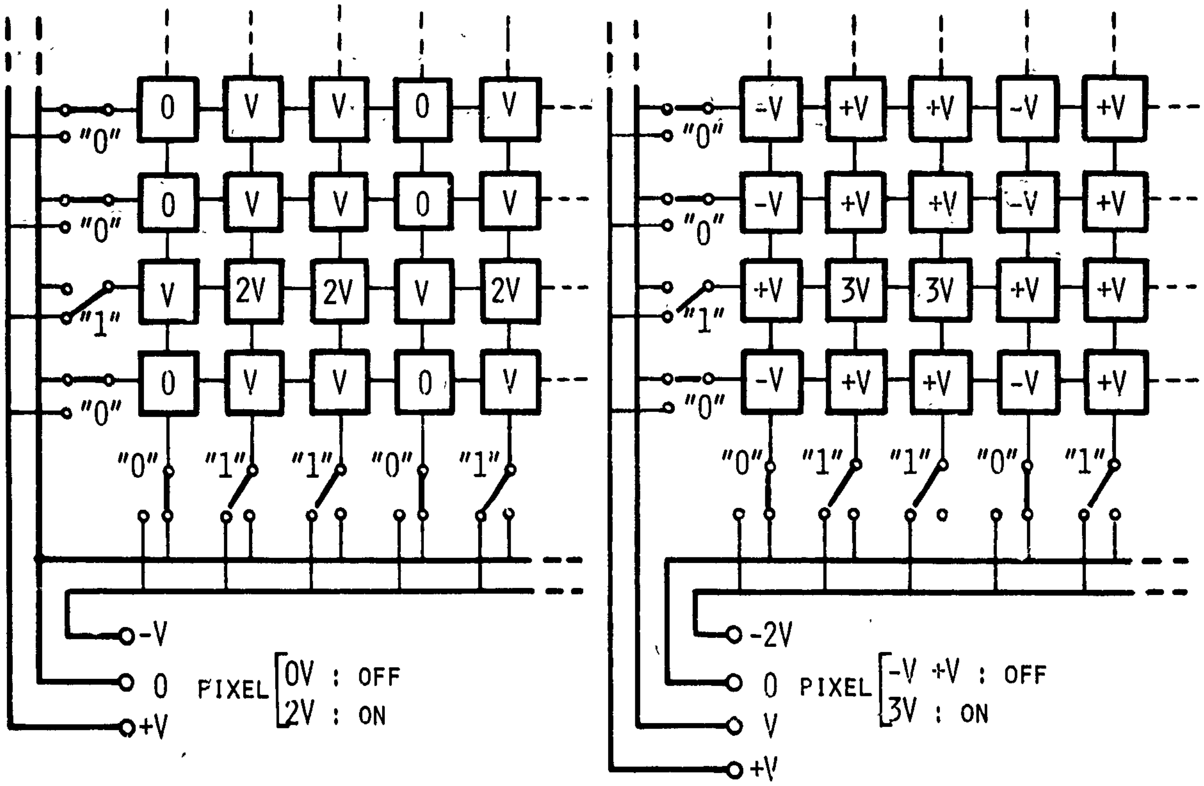


Fig.2.6 Number of pixels vs screensize for several application areas



A

HALF-SELECTION SCHEME

B

THIRD-SELECTION SCHEME

Fig.2.7 Display matrix scanning techniques

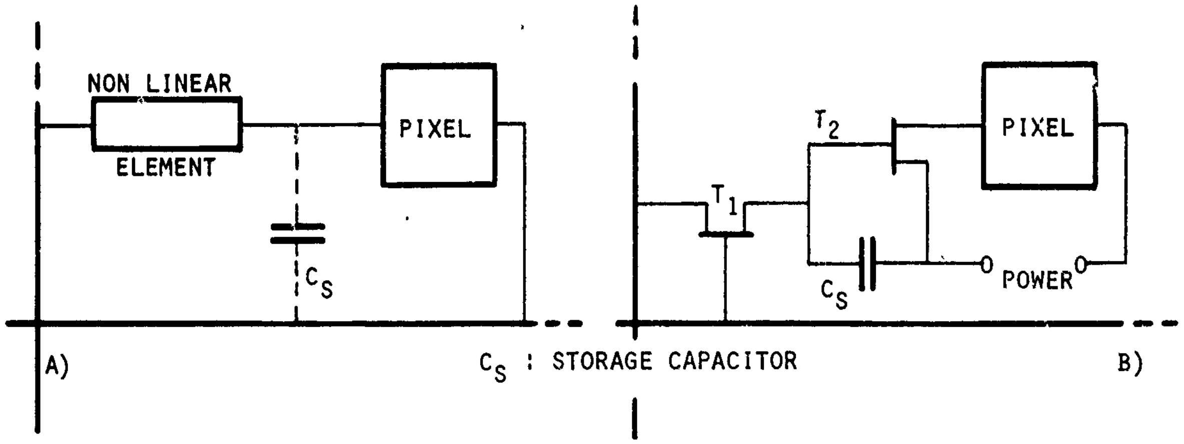


Fig.2.8 Addressing/driving the picture elements of matrix displays

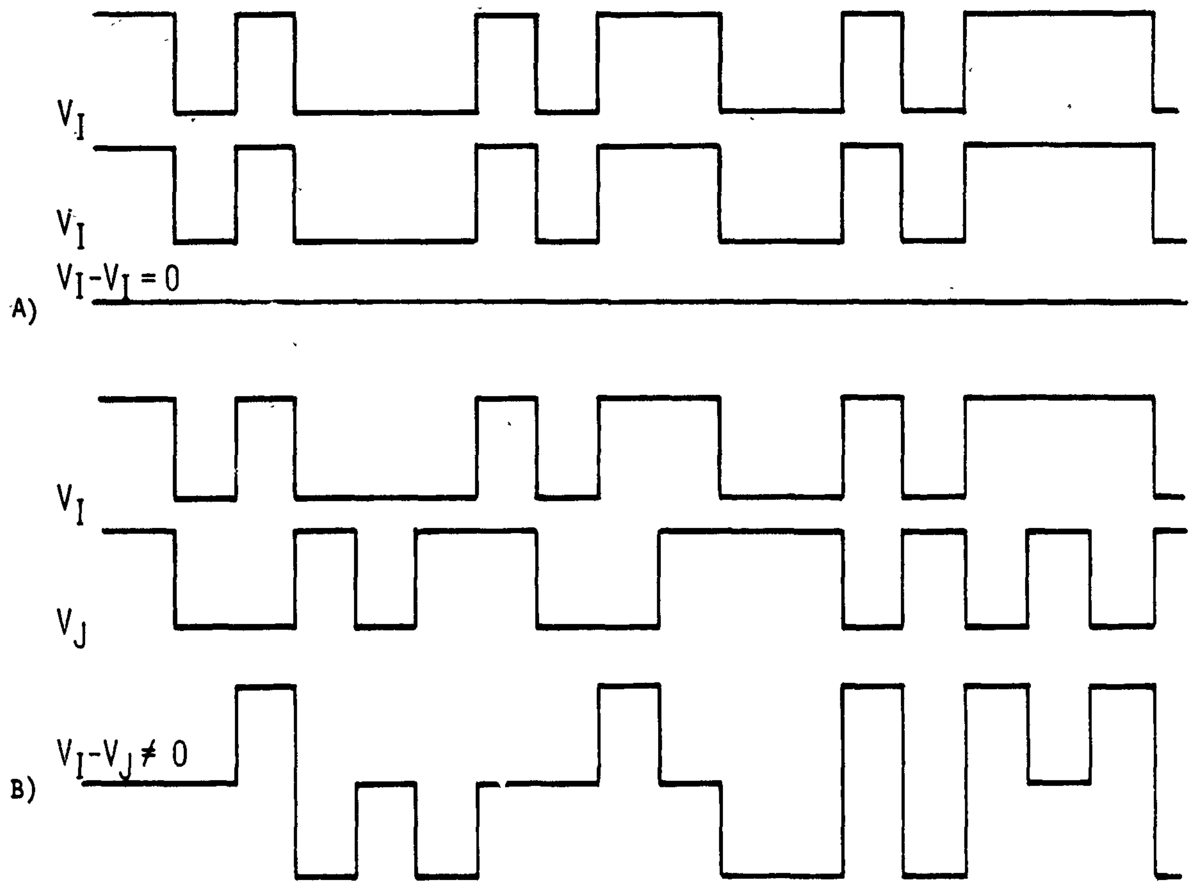


Fig.2.9 Waveforms in pseudo random binary sequence addressing scheme

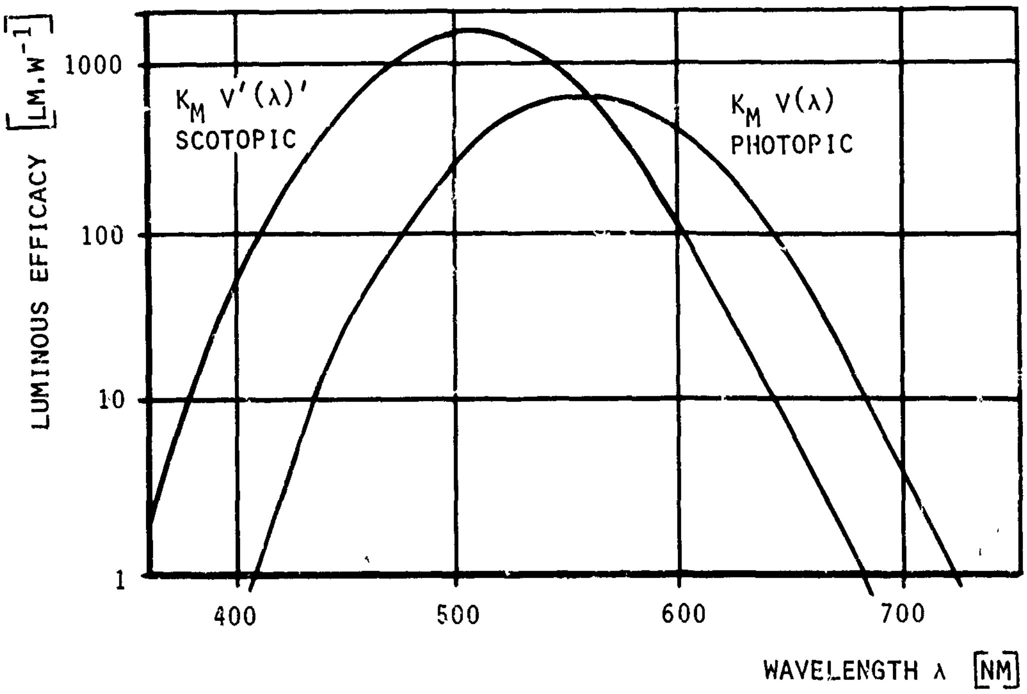


Fig.2.10 Luminous efficacy K_m V(λ) or K_m' V'(λ) of the human eye

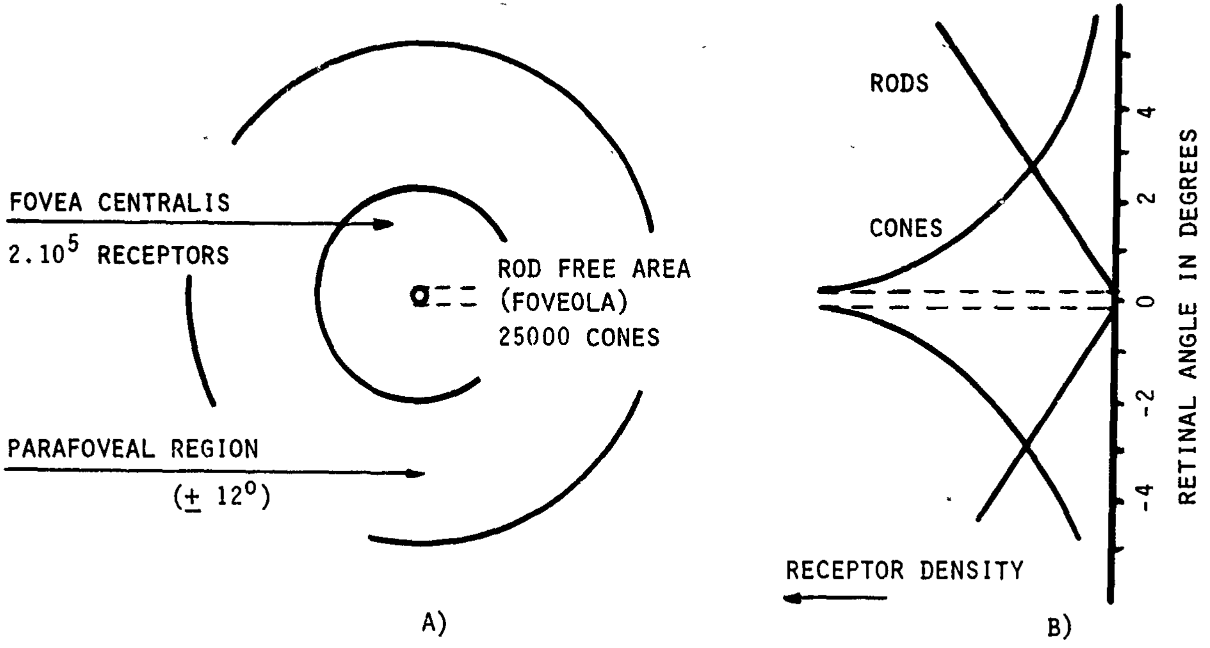


Fig.2.11 Retinal regions: (a) density distributions of cones and rods

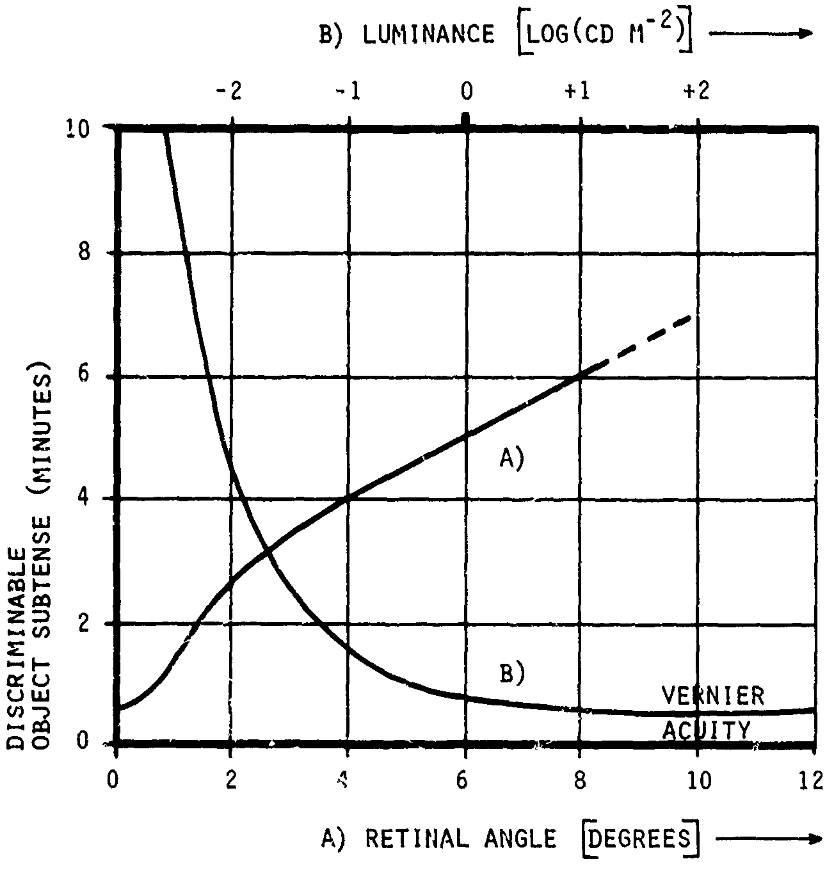


Fig.2.12 Static visual acuity: (a) as a function of the distance from the centre of the fovea;
(b) as a function of luminance, for foveal view. Both at 100% contrast (C_V)

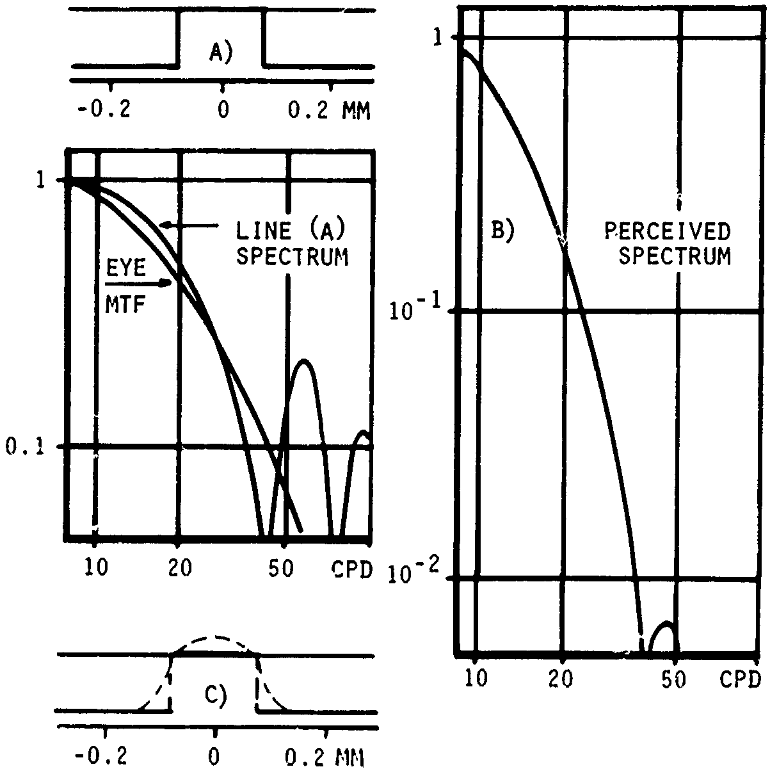


Fig.2.13 Mollified perception (c) of line with sharp edges
(a) through attenuation of spatial high frequency components
(b) on its spectrum (a) by the MTF of the eye

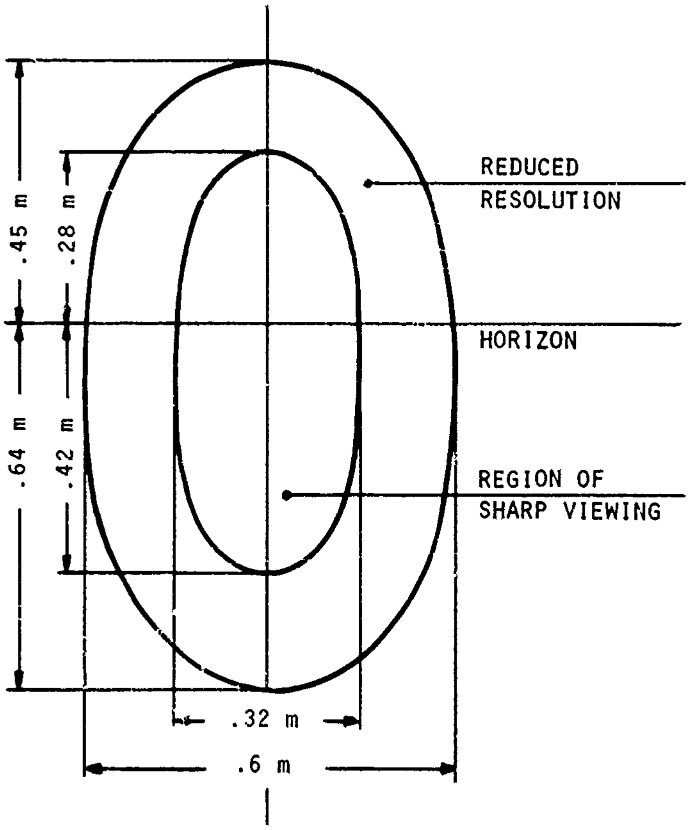


Fig.2.14 Viewing area, at 0.7 m viewing distance, covered with eye movements only

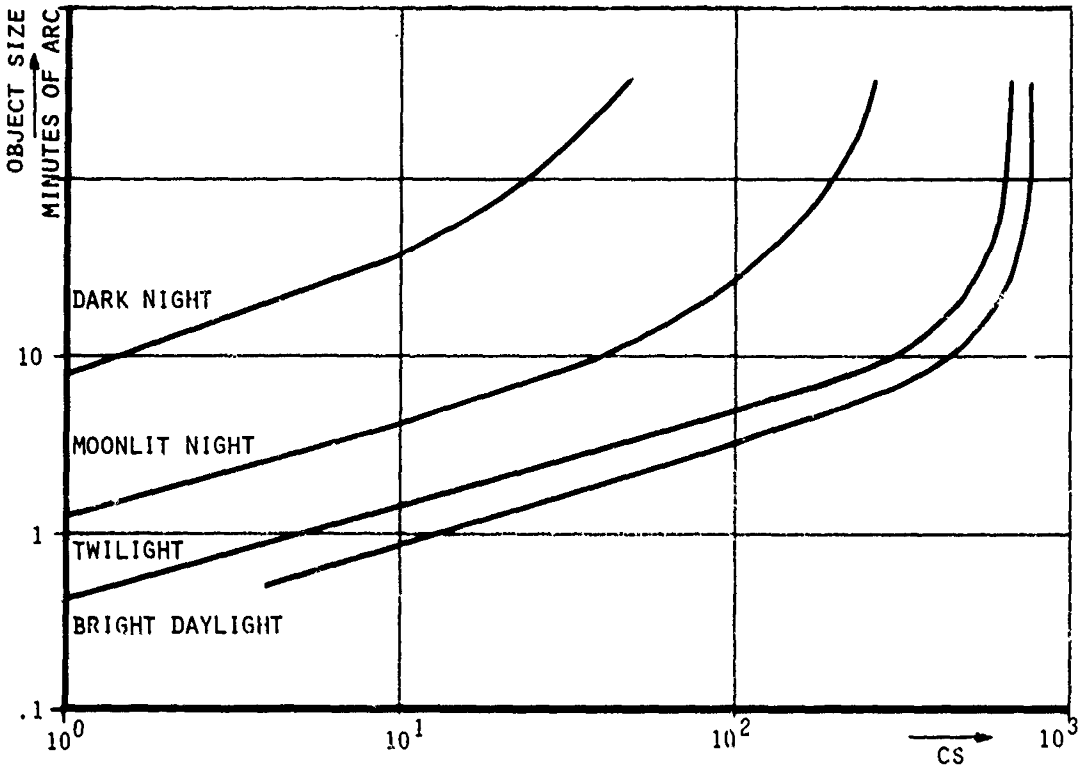


Fig.2.15 Contrast threshold vs visual angle at four adaptation levels of the average human eye

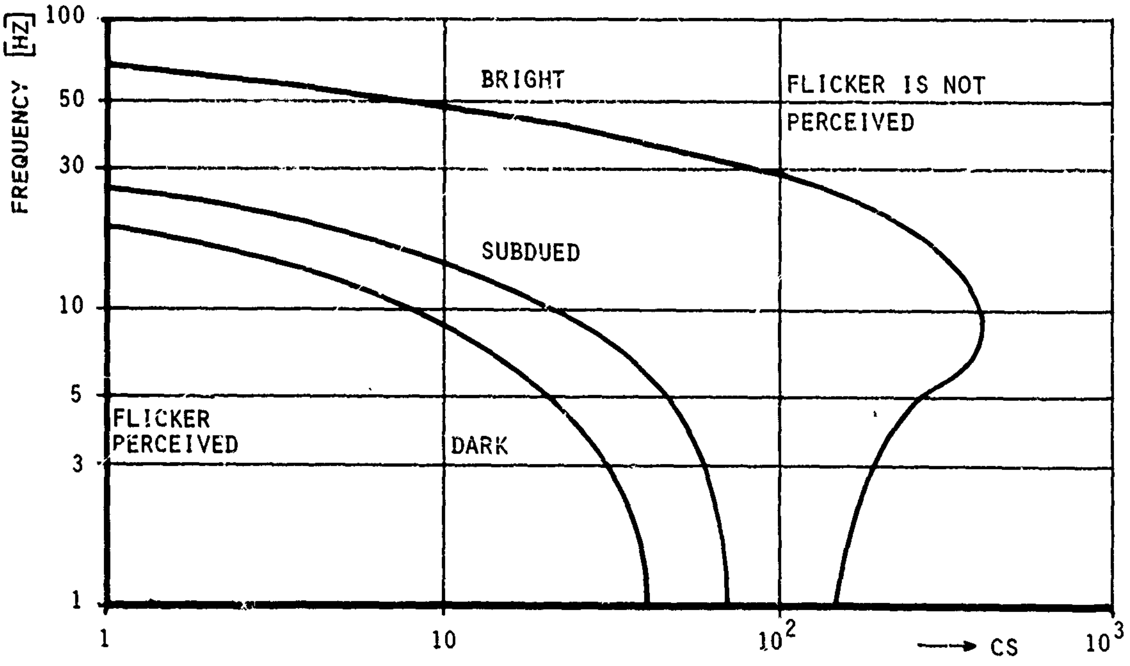


Fig.2.16 Curves of apparent flicker fusion of a small flickering field in a large, constant, background; at three levels of brightness

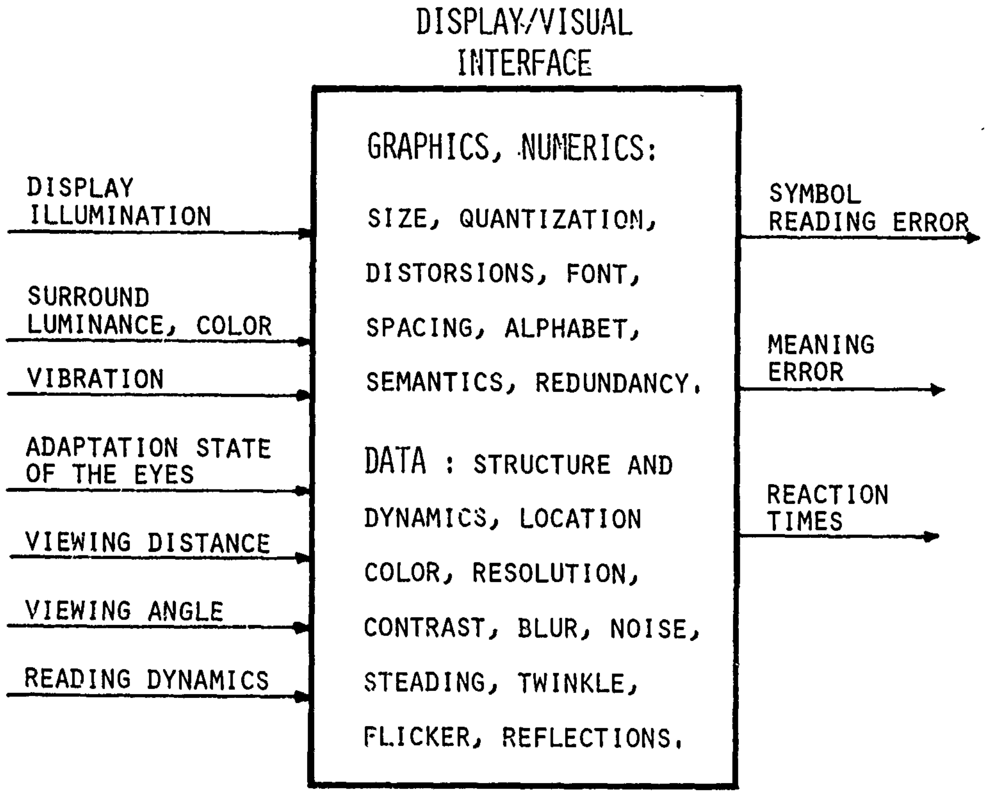


Fig.2.17 Legibility performance factors

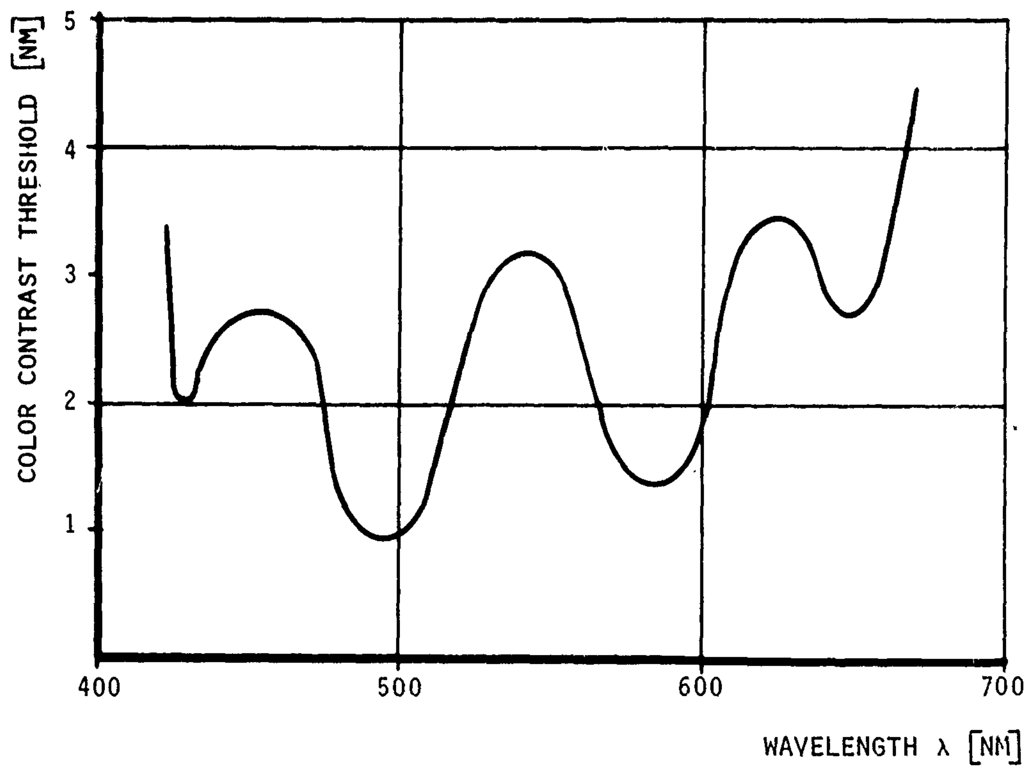


Fig.2.18 Wavelength discrimination (JND) detected as different hue, under specified conditions

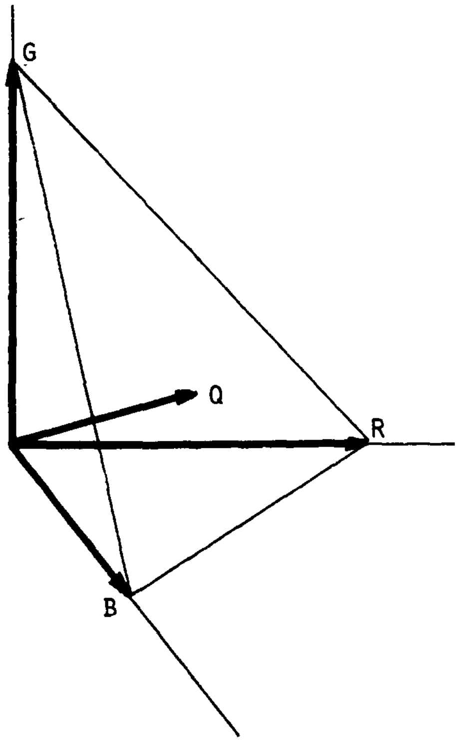


Fig.2.19 R. G, B color space

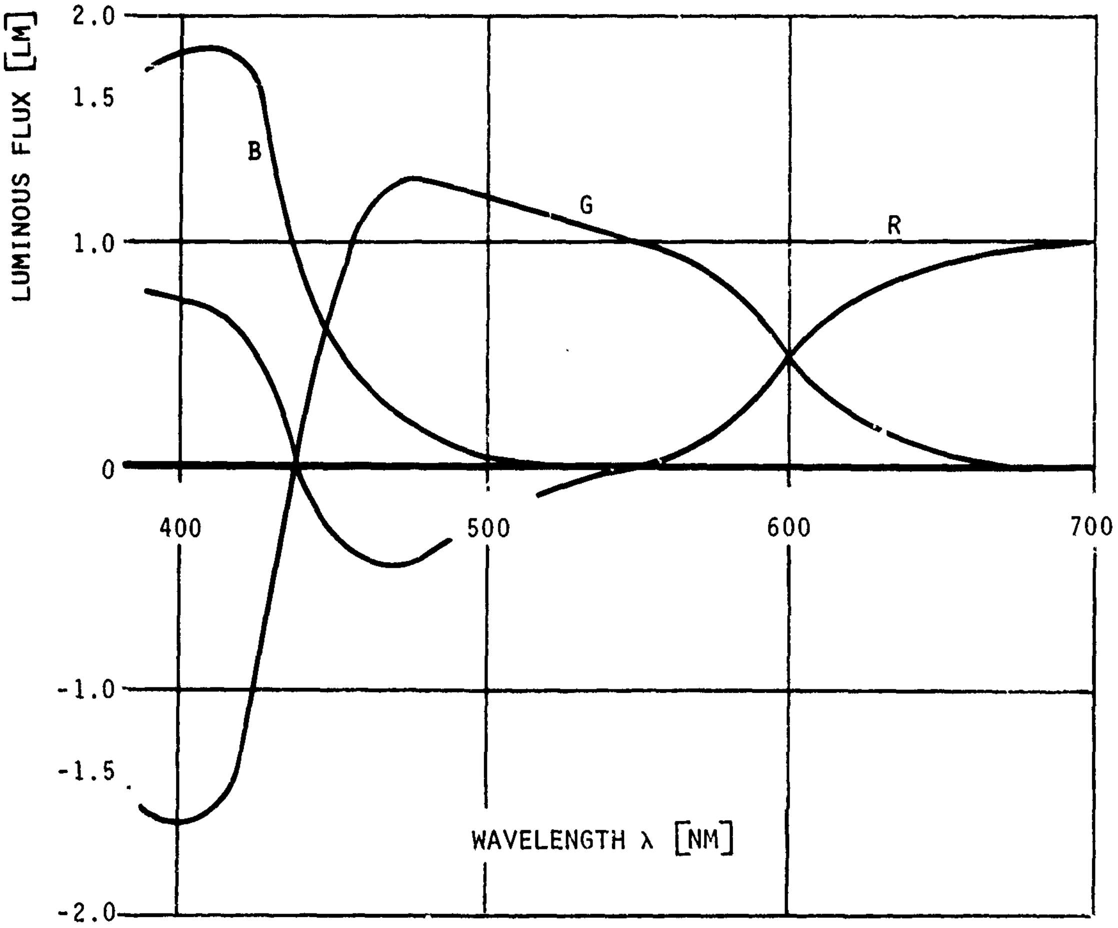


Fig.2.20 Tristimulus values for spectral colors in normalized R, G, B system

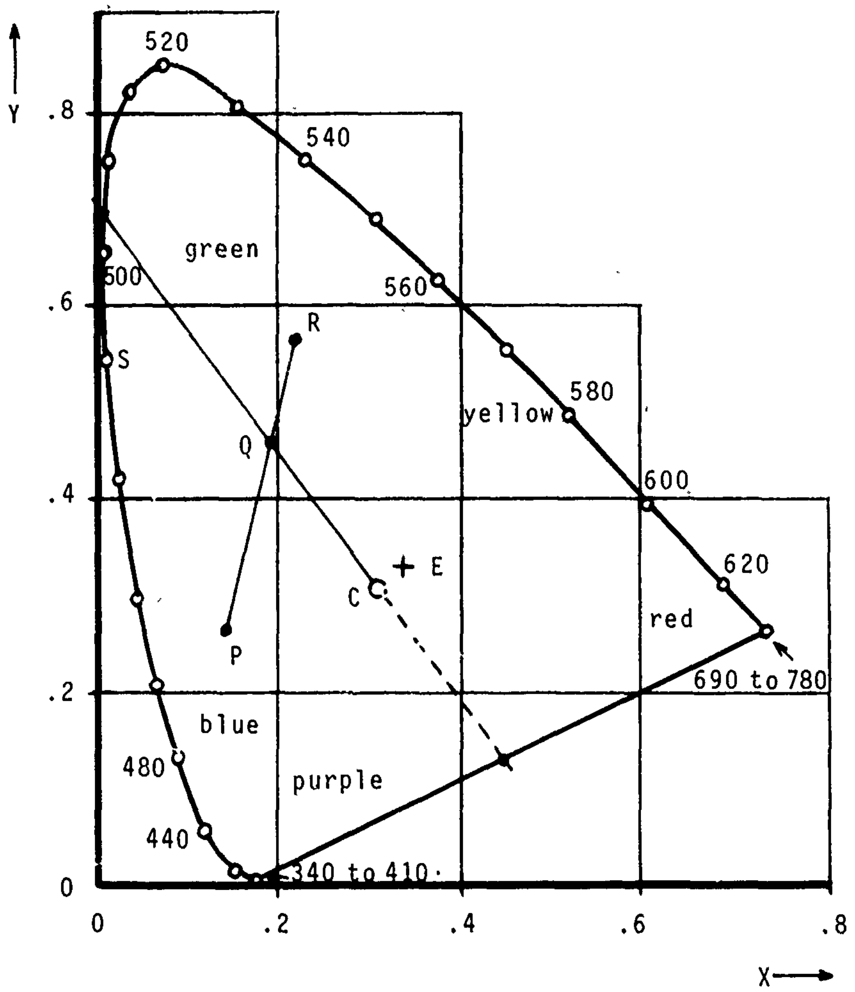


Fig.2.21 CEI x, y chromaticity diagram

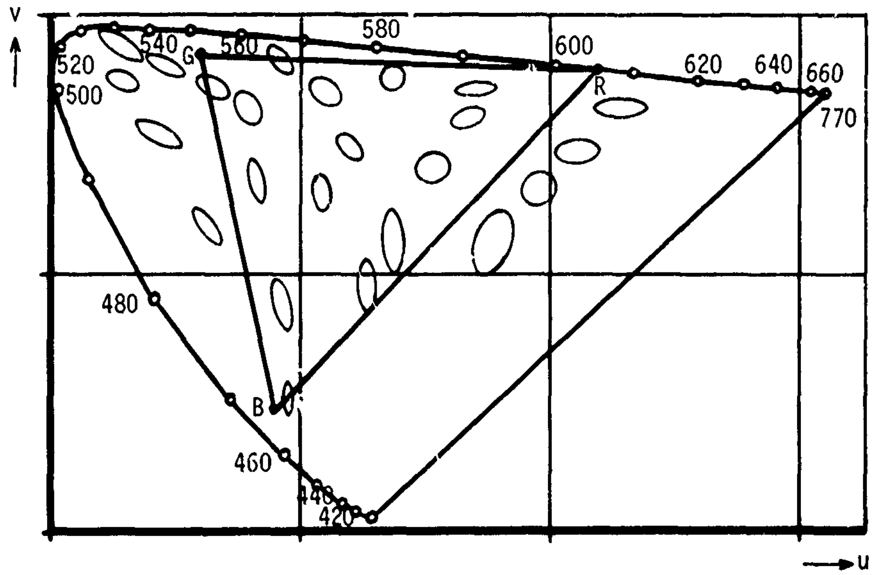


Fig.2.22 CEI/UCS diagram showing JND (McAdam) ellipses (10 x actual size). The triangle RGB represents addressable hues of a shadow mask CPT

CHAPTER 3, TECHNOLOGIES

3.1 CATHODE RAY TUBES

3.1.1 HISTORICAL SURVEY

The cathode ray tube (CRT) is one of the earliest electro-optical devices, and its name derives from experiments in which a greenish glow was produced on the glass surface of an evacuated tube when a high potential caused electrons to be stripped from the cathode and to strike the glass. Although 'electron beam tube' would be a much more accurate description the earlier name is so well established that it is unlikely ever to be displaced.

The phenomenon that cathode rays (electron beams) are deflected by electric and magnetic fields led to the use of the tube as a laboratory measuring device. The successive developments to transform this simple device into a practical display include the incorporation of a flat phosphor display screen and the use of a heated filament cathode. By 1908 Campbell Swinton was suggesting the use of the CRT for transmitting and reproducing television images, and during the 1920s and 1930s the CRT was used in much of the radio and electronic research then under way.

Use of the CRT in aircraft dates back to the late 1930s, when airborne radar and electronic navigation systems incorporated CRTs as displays for the equipment operators (3.1.1). These tubes were always cursively-written, a technique similar to laboratory oscilloscope writing and quite distinct from TV raster type of presentation which has only come into use in aircraft quite recently. Development of CRTs since that time has steadily progressed so that a wide range of monochrome tubes is now available for use in many different applications (3.1.2).

Multicolour CRTs are a much more recent development. The first scheme to be taken to the stage of large-scale production was the RCA shadowmask on which development was started in 1949 and which went into production in 1954, although during the period 1954 to 1968 there were still many important advances made in manufacturing technology and tube characteristics. Since 1968 further improvements include the introduction of the Trinitron and the black-matrix phosphor screen, as well as the appearance of the penetration tube as a viable colour tube contender albeit with a more limited colour range. The use of colour CRTs for the display of information in aircraft cockpits is relatively recent, but it appears likely that most civil aircraft will use them extensively in the relatively near future, followed by military aircraft applications within a few years (3.1.3).

3.1.2 PRINCIPLES OF OPERATION

3.1.2.1 Monochrome tubes

The basic principle of the CRT in its most simple form is shown in Fig. 3.1.1. The main structure consists of an evacuated envelope in the form of a glass or metal bottle with a narrow neck flaring towards the front display surface which, for aircraft application, is generally of rectangular shape. Within the neck is an electron gun which projects a beam of electrons towards the phosphor screen deposited on the front surface, the electrons being accelerated by the large potential difference (typically in the range 10 kV to 30 kV) established between the gun and the anodes and screen. The beam is deflected so that it can strike any part of the screen, and is modulated in intensity so as to vary the perceived luminance of the screen.

Several variants of gun design are possible. For airborne application the principal requirement is to obtain a well defined and narrow beam with high current density, and this leads to the types of design shown in Fig. 3.1.1. Limitation of electronic current density emitted from the surface of conventional oxide-coated cathodes is a major factor in determining the beam density, and for this reason alternatives are currently being sought such as the dispenser cathode. Within the gun structure a grid or modulator is fitted such that variation of the grid voltage controls the beam current.

Deflection of the beam can be achieved either electrostatically or magnetically. The choice between these two techniques is a complex one, but for airborne use when high screen luminance, high resolution and large scan angles are required, it is necessary to use magnetic deflection.

The coils required to achieve this are shown in Fig. 3.1.1, and are generally arranged in pairs such that magnetic fields can be produced in two orthogonal directions which are also orthogonal to the tube axis. Suitable currents through the pairs of coils then allow the beam to be deflected in both directions across the screen surface using the addressing techniques discussed below. In addition, magnetic coils may also be used for beam focussing and to compensate for aberrations in the electron optics.

Magnetic focus was used in early airborne displays and is still used in several up-to-date applications. Theoretically, this gives the best possible resolution but requires very careful and elaborate adjustment to obtain the theoretical optimum. Improvements in electrostatic focus design have, however, resulted in spot sizes which are very similar to those which can be achieved in practice using magnetic focus. In addition, electrostatic focus results in considerable weight saving and ease of replacement of tubes. Electrostatic focus is achieved either by means of an einzel lens (low voltage focus) or by a bi-potential lens (high voltage focus).

The process by which light is emitted from material when excited by high-energy electrons is called cathodo-luminescence, and the material is normally described as a phosphor. Many crystalline materials have been used as phosphors and are commonly based on zinc sulphide although recently there has been much use of the rare earth activated oxides and oxysulphides. The main factors to be considered in the choice of phosphor are luminous efficiency, decay time, colour and life. The values of luminous efficiency are generally in the range 10 to 50 lm/W, with the higher values being for emissions in the geeen wavelengths where the eye has maximum sensitivity. These efficiency values are a factor of 10 or more greater than those for other types of electroluminescence, which is one of the principal reasons for the continued pre-eminence of CRTs for many applications. Phosphor decay times range from less than a microsecond to several seconds, the longer persistance phosphors allowing significant integration which can be valuable for reducing or eliminating flicker and noise in relatively stationary images, but cause smearing of dynamic images. Phosphors can be obtained for all colours in the visible spectrum, and for enough of the spectral triangle to allow reasonable reproduction of most colours. As for life, it is possible to de-sensitise phosphors by excessive beam current, but for most practical current levels phosphors are now available with lives of several thousand hours provided they are operated over the linear part of their operating characteristics.

The simple CRT described above produces a monochrome picture, the colour of which is determined by the phosphor characteristics. The generation of a multi-colour picture is a more difficult task and requires a significant complication of the basic tube technique. Several alternative methods of producing colour pictures have been devised and the most promising of these are described below.

3.1.2.2 Shadowmask colour tubes

The type of colour CRT which has been most extensively used, particularly in domestic colour TV sets, is the shadowmask. The basic arrangement of this is shown in Fig. 3.1.2. As compared with the monochrome tube, the principal changes are the provision of three guns, the addition of the shadowmask, and the patterning of the phosphor screen.

The phosphor screen is printed in the form of an array of 'triads', each triad consisting of a dot of each of the primary phosphor colours, red, green and blue. The geometry of the guns, shadowmask and screen is arranged so that the beam from each gun can fall on only one coloured dot in each triad, the other two colours being masked from the gun by the shadowmask. Thus the three guns can be independently fed with the required modulation signals of the three primary colours. The three beams pass through the same magnetic deflection coils with the same electron velocities and are therefore deflected together, by approximately the same amount, and the electrostatic focus elements are generally also common so that a single focus control is sufficient.

This arrangement requires very exact alignment of the guns, mask and phosphor pattern, but the high yield and low cost in large-scale production are clear evidence that the alignment techniques are now well established. The most recent developments in shadowmask CRTs for the domestic market have concentrated principally upon improving the visual contrast through the use of a black matrix screen to fill in the areas between the phosphor dots, the reduction in length of tube by increasing beam deflection angles and the introduction of in-line guns. This type of gun arrangement has also been used in conjunction with striped phosphor patterns and slotted shadowmasks such as in the 'Trinitron' CRT.

In the context of airborne applications, the principle difficulties arise due to lack of luminance and to environmental limitations. Considerable loss of electron-beam current occurs at the shadowmask, so that typically only 15-30% of the average beam current reaches the phosphor. Apart from the loss of luminance this also creates the problem in high brightness tubes that the energy absorbed in the shadowmask can cause thermal expansion and thereby upset the exact alignment between shadowmask and phosphor screen. The second luminance problem arises because the luminous efficiency of red and blue phosphors is significantly less than for high efficiency green phosphors. A third difficulty is that with monochrome tubes low luminance can to some extent be compensated by using narrow-band coloured filters in front of the tube to minimise reflection, whereas with shadowmask and other colour tubes it is not easy to produce filters to match all three phosphor colours. For these reasons, airborne shadowmask tubes have not yet fully matched the high luminance requirements of military users although they are now finding increasing use in civil aircraft.

Application in the aircraft cockpit environment also creates vibration problems. The shadowmask is necessarily a thin and rather flimsy structure, which can be excited into resonances by external vibration, with consequent effect upon alignment and therefore upon the tube's colour purity. These problems have been substantially solved for the civil aircraft vibration levels, and recent developments suggest that rugged tubes suitable for military aircraft environments may soon be available.

3.1.2.3 Beam index colour tubes

An alternative to the shadowmask tube which is similar in some respects but avoids the structural problems of the shadowmask is the beam-index tube (3.1.4), (3.1.5). This is shown in Fig. 3.1.3. The phosphor screen is arranged in a pattern of stripes similar to those of the 'Trinitron' CRT, but instead of using a mechanical mask to ensure that only the correct phosphor is energised by the beam, it uses electronic control. A single gun is used and the beam is scanned across the stripes in a raster mode (cursive writing is not generally possible), the beam current being modulated so that the appropriate levels of current are used to excite each of the three colours in turn. To achieve good colour purity the beam width must be very narrow, and the beam modulation must be exactly synchronised to the beam position. This synchronisation is achieved by putting onto the rear of the phosphor a fourth series of stripes in the form of a UV or X-ray emitting phosphor. In each case the emission is detected and its timing is used to synchronise the beam current modulator to the scan deflection waveform, through the fast acting control loop. An alternative method of obtaining the synchronisation signal has been described by Turner (3.1.6); this uses a pattern on the aluminium film behind the phosphor screen to generate a signal in the return beam-current from the film.

The considerable mechanical simplification inherent in the beam-index tube is obtained at the cost of electronic complexity. At the present time, in spite of many attempts to develop a viable tube of this type, the difficulty of making a control loop with the required phase stability at high frequency, together with colour purity and brightness problems, have prevented this type of tube from being exploited on a production basis.

3.1.2.4 Penetration phosphor tube

The third technique for colour CRTs is the Beam Penetration or 'Penetron' tube, which is also of much simpler construction than the shadowmask type. Its construction is generally similar to that of the monochrome tube shown in Fig. 3.1.1, but the colour characteristics are obtained by the particular characteristics of the phosphor screen (3.1.7).

In one arrangement of the screen it is formed of a combination of two types of phosphor material, one of which is generally chosen to emit green light and the other of which emits red light. The green phosphor particles are coated with an 'onion-skin' of barrier material and then further coated with a layer of red phosphor. It is also arranged that the EHT potential applied to the screen can be set at any value between upper and lower limits which are typically 17 kV and 10 kV. At the lower limit the beam current electrons are unable to penetrate the barrier layer surrounding the green phosphor particles, and only red light is emitted from the screen due to electron excitation of the red phosphor material. At the higher EHT limit the electrons penetrate the barrier and excite the green phosphor particles, so that both green and red emissions are produced. However because the efficiency of the green phosphor material is generally greater than that of the red, the resultant colour is a reasonably pure green.

For intermediate EHT values, a range of different colours is obtained resulting from the addition of red and green in different proportions. However the use of only these two primary colours necessarily restricts the range of colours which may be generated to a single line on the colour triangle, and in fact it is generally possible to produce only four distinct colours (red, orange, yellow and green), and in high ambient illumination possibly only three. Other spectral characteristics can be obtained by the use of different phosphors, and variations in temporal characteristics are also possible by choosing phosphors with different storage/decay properties.

The principal advantages of this type of tube as compared with the shadowmask tube are the rugged mechanical construction and the high resolution. The absence of any fragile component such as the shadowmask, or of the need for accurate geometrical registration, means that it can be used in any vibration environment for which a monochrome tube is suitable, *ie* any reasonable cockpit environment. Also, the absence of any pattern on the phosphor screen means that tube resolution is limited by beam width rather than by the size of the phosphor spots or lines, so that high resolution is possible. Patterned contrast filters can also be used without forming moiré fringing effects.

Although the luminance is not reduced by the same mechanisms as in the shadowmask tube, it is still significantly below that of the monochrome CRT. This is principally for the red colour, and is due in part to the relative inefficiencies of red phosphors and also due to the low excitation voltage. Moreover the green colour is also generated inefficiently, by comparison with monochrome CRTs, mainly due to energy loss in the barrier coating.

As with the beam-index tube, mechanical simplicity is obtained at the cost of electrical complexity. It is necessary to switch high EHT voltages at fairly high speeds, and in addition the deflection sensitivity and focus change with EHT so that it is necessary also to change the current conditions in these circuits. In practice it has been found impractical to alter all these circuit conditions in the 100 ns which would be necessary if colour variations were to be produced during the writing of a raster TV frame, and this type of tube is normally operated in a field-sequential colour switching mode, which complicates the design and can lead to colour flicker problems. For cursively written data the colour can be changed between groups of characters and symbols.

3.1.2.5 Other colour display techniques

For completeness it is convenient to mention here two other techniques which are applicable to a range of displays and are not specific to CRTs.

The first of these is the field-sequential colour filter, previously described by Shanks (3.1.8). A CRT display incorporating a white or multi-colour phosphor is viewed through a filter screen made of a material such as a liquid crystal, which is arranged so that using its birefrigent characteristics it can be switched to pass a different colour of light depending on the voltage applied to it. Such a display/filter combination can be made very rugged and of reasonable brightness. Most arrangements of the liquid crystal filter permit the use of only two principal colours, and the principal disadvantages are then similar to those of the penetration tube, a limited colour range based on the two principal colours, and the possibility of colour flicker due to field-sequential colour switching. Difficulties have also been found in producing large liquid crystal panels of good cosmetic appearance.

Another method is to optically combine the optical outputs from two or three CRT display surfaces of different colours. The 'COMED' display (3.1.9) uses lenses and mirrors to combine a monochrome CRT and an illuminated map and a similar arrangement could be used with any display surfaces. The use of optical combination implies limited viewing angles and hence is particularly appropriate to single or tandem-seat military aircraft, where a reduced brightness can be made acceptable by correct positioning of the exit pupil. However such a display has not yet been used in aircraft, due presumably to the penalties of volume and complexity.

3.1.3 PHYSICAL CHARACTERISTICS

The overall shape of displays using CRTs is generally determined by the shape of the CRT itself, and because of the fundamental nature of the deflected electron beam mechanism for addressing the display surface, this shape is generally that of a long-necked bottle at the rear of the surface. The depth of the tube is determined by the maximum deflection angle of the electron beam, and in practice for airborne tubes this does not normally exceed 70^{o} because of defocussing and power consumption characteristics. For a typical gun size this results in an overall tube length about 1.2 times the screen diagonal dimension (*eg* a length of 300 mm with a screen of 175 mm × 175 mm). The screen's usable area is less than the overall area of the front glass surface, a non-usable border of 10 mm being typical.

The shape of the tube and in particular the narrow neck allow much of the associated electrical circuits and deflection coils to be mounted within a rectangular package very little larger than the overall tube dimensions, although if vibration isolation is required this may increase the space requirement. Displays using optical components, such as head-up displays or projection displays, have geometries designed to suit the optics as much as the CRT itself.

For aircraft use, as direct view displays, screen sizes are typically in the range 50 mm diagonal to 300 mm diagonal, and are usually rectangular or square in shape. Head-up displays use circular screens up to 100 mm diameter. CRTs for helmet-mounted displays have been developed (3.1.10), and with these it is necessary to minimise both weight and size of the CRT; a typical tube has a 20 mm diameter useful screen and a length of 100 mm.

The requirement for high EHT voltages might be thought to create difficulties, especially with breakdown at high altitudes, but design techniques have evolved so that up to 25 kV is now considered standard practice. Similarly, the use of a large evacuated glass tube, which might be thought operationally undesirable, has not in practice caused real problems, and although tubes have been constructed using metal and ceramic envelopes this is now not generally necessary. However for use in military aircraft, care has to be taken with the mounting arrangements and tubes are sometimes manufactured with an integral metal mounting collar or frame.

When used with the higher levels of EHT voltage there is necessarily some X-ray generation at the screen, but it is rarely necessary to incorporate within the display a specific filter to absorb this radiation, since the use of lead glass faceplates ensures that the emitted radiation is within the permissible level.

Because of the relatively large size of the tube, and the use of magnetic and high voltage components, the weight of displays based on CRTs is generally rather large. Thus for example an airborne 200 mm × 150 mm display suitable for a military aircraft could typically weigh 7.5 kg; this could be a significant weight penalty for small aircraft and helicopters.

3.1.4 ADDRESSING/DRIVING

The monochrome CRT described above has a uniform screen face which can be energised instantaneously at one spot only, the position of that spot being determined by analogue currents in the X and Y deflection coils (or in the case of electro-static deflection by potentials on the X and Y plates). Therefore to produce a complete 'frame' of information, the spot must be deflected according to some pattern, which may cover all or part of the whole screen, and upon completion of the pattern it must within a short period restart the process and write the next pattern. Because of the response characteristics of the eye the frames are usually written at repetition frequencies of 50 Hz or more, so that the screen appears to emit continuously and little or no flicker is perceived.

Two alternative types of scanning pattern are available, generally known as the raster and cursive techniques.

In the raster method the spot always follows a fixed pattern of parallel straight lines, spaced closely together, to cover the whole screen area. The lines are usually horizontal and written from the top of the screen to the bottom. The picture or symbolic message is then written by modulating the beam current so that the emitted luminance can be varied independently at any point on the screen. The modulation can either be simple 'on-off' to produce the equivalent of a black-white screen picture, or can be continuously varied by an analogue input signal to produce a 'shades of gray' picture.

Standards for raster writing have evolved largely from television systems, and for airborne use the proposed NATO standards comprise two alternatives. These are 625 lines at 50 fields per second, interlaced 2:1, and 875 lines at 60 fields per second, interlaced 2:1. The latter standard, which is only justified in aircraft cockpit use with fairly large display sizes, requires that the modulation signal has a bandwidth of 15-20 MHz if the inherent resolution of the line standard is to be used. One of the principal advantages of raster operation is that the deflection currents follow a set pattern and the deflection circuits can have a relatively low bandwidth, 50-100 kHz being typical with a high Q circuit, and this results in lower energy losses in the deflection system than for cursive operation at typical writing speeds.

The cursive method of writing allows the spot to travel over the screen face in random directions. Generally this technique is used with a fixed beam current, so that provided the spot velocity is constant the brightness of the resultant lines is also uniform. The method is particularly useful for line writing and is only secondarily used for area shading, but the written lines can be either straight or curved and may include a repertoire of fixed characters. Because of the random nature of the writing pattern there are no accepted standards, although frame refresh frequencies of around 50 Hz are generally used in order to satisfy flicker perception requirements. Writing speeds depend upon the amount of data to be displayed, and are typically in the range 30-100 m/s.

The need for uniform spot velocity with a randomly moving spot implies that resonant deflection circuits cannot be used and that broad-band operation of these circuits is necessary with consequent power losses. The use of colour tubes introduces some complications. Shadowmask tubes written in raster or cursive mode merely require three modulation signals to the three independent guns. Penetration tubes written in raster mode require alternate frames to be written in one of the two phosphor colours, and therefore the EHT must be switched between frames. In addition it should be noted that the standards for raster writing mentioned above are not appropriate for this type of tube because the use of sequential colour fields at frame frequencies of 25 to 30 frames per second is likely to introduce colour flicker. A further complication with raster operation is that the need to rapidly switch the EHT requires considerable energy and robust components because of the input capacity of the CRT. In practice, penetration tubes are usually driven cursively, and the added complications take the form of an EHT power supply which can switch in about 1 ms, together with deflection and focus circuits which can cope with the variations in tube sensitivity caused by the changes in EHT voltage.

3.1.5 SYSTEM INTERFACE

The information which is fed to airborne CRT displays is usually either of a pictorial nature and is derived from a sensor such as TV, Forward-Looking Infra-Red (FLIR) or radar, or is a quantitative parameter such as airspeed, height or fuel content.

In the former case it is customary to select a standard display format such as the raster formats described above, and to define this as the output from the sensor package. Thus for example with scan-converted radar the scan conversion takes place within the radar and the output conforms to the display standard, thus minimising interfacing problems at the display itself.

For quantitative data it is necessary to accept this data into the display system in analogue or digital form and it then has to be converted into a form suitable for feeding to the CRT deflection and modulation amplifiers. The information may be presented in analogue or numerical form and in the former case may be as a scale, a vector or a pointer. Special interface units known as waveform generators are used for this conversion and can be made for either raster or cursive operation.

Although early waveform generators were generally made up of dedicated hardware elements to perform specific roles of character generation, axis transformation, etc, it has recently become possible to use the high speed capabilities of modern digital processors to carry out all the functions in a general purpose computer in which all the required characters and symbols are defined by software. The availability of large (*eg* 64K) random access memories at low cost is important in this type of design as it enables a store location to be assigned to each picture point in the display with the content of the store being updated at intervals from the computer. Modern techniques such as this have the advantage that formats can be modified by software and as memory costs reduce even further they are likely to become the standard form of waveform generator for the future. The store is read out at fixed intervals and may be modified to improve the cosmetic appearance of lines or symbols before being converted to analogue form to be fed to the deflection and modulation amplifiers. When a combination of symbolic and pictorial information is to be presented, the appropriate signals can be mixed together either in the digital store or at the analogue stage.

3.1.6 VISUAL CHARACTERISTICS

3.1.6.1 Resolution

The phosphor screen is made up of a layer of fine granules of the phosphor material, typically of around 10 µm diameter and except in the case of the smallest tubes the size of these should not be significant in determining tube resolution. For monochrome tubes, therefore, the resolution of the image on the screen is principally determined by the diameter of the electron beam and spot-spread within the phosphor, and by the resolution characteristics inherent in the beam-writing pattern. In practice, for raster displays, these two factors tend to be approximately equal; clearly there is no merit in making either factor grossly different from the other. Therefore for raster tubes operated at the TV line standards described in section 3.1.4 above, a resolution of 600-800 lines vertically is obtained and with a circular spot and adequate bandwidth in the video signal the horizontal resolution is in the region of 1000-1200 TV lines (500-600 cycles).

For signals of varying modulation level it is customary to use as a measure of horizontal resolution the modulation transfer function (MTF), which is generally a decreasing function of spatial frequency. Experimental measurements of MTF frequently show that the useful spatial frequency for low contrast signals is significantly less than expected from simple resolution calculations. An example of the use of MTF methods is provided in Ref. 3.1.11, this paper being of particular interest in indicating the resolution obtainable from the small CRTs used in helmet-mounted displays. Under favourable conditions up to 600 cycles per horizontal line can be obtained at 50% MTF on a 25mm diameter tube. Fig. 3.1.4 shows MTF curves for larger tubes, and is taken from Banbury and Whitfield's paper (3.1.12) which provides a useful guide to the measurement of MTF of CRTs.

For cursively-written CRTs the line width effectively defines resolution, and thus is principally a function of electron-beam width and of spot-spreading in the phosphor. At the high current densities used in head-up displays, spreading can be significant, but with well-focussed tubes and at lower current densities the width of a line-pair can generally be made below that which can be resolved by the eye.

A comparison of the resolution of colour CRT types has been made by Brun and Martin (3.1.13). For penetration colour tubes the situation is similar to monochrome, except that the size of phosphor granules tends to be a little larger than for monochrome tubes and may be a little more apparent. For shadowmask tubes the phosphor pattern has a very real effect on resolution, especially in the case of cursively-written symbology. If a narrow line is written across a shadowmask tube, coloured moiré patterns are produced at low spatial frequencies because of the discrete nature of the screen, and the electron beam therefore has to be widened to about twice the triad pitch. This could be a major problem in the use of shadowmask tubes for high resolution airborne displays.

Finally it may be noted that when lines are drawn at an angle to the scan lines on a raster display the line structure can cause an apparent series of steps in the line. Although this is an inherent characteristic of raster CRTs the effect can be minimised by shading each edge of the drawn line on the raster lines, so that the steps are less obtrusive and the display appears to have higher spatial resolution than it really has.

Nevertheless it is generally accepted that cursively-written displays appear sharper than raster displays of lines or symbols.

3.1.6.2 Brightness and contrast

One of the major problems in the airborne use of CRTs derives directly from the reflection characteristics of the phosphor screen. The screen acts as a high efficiency, approximately Lambertian, reflector such that over 75% of the light incident upon it is scattered back from its surface, and the light emitted from the phosphor is perceived against this uniform background. In a light ambient of 10^5 lux, the display surface can have an apparent luminance of 3×10^4 cd m^{-2} so that to obtain a display contrast of 10 the luminance of the excited phosphor would need to be 3×10^5 cd m^{-2}, a very high figure even for high efficiency phosphor. For this reason it is usually necessary with both raster and cursively-written displays to insert a filter between the screen and the viewer to attenuate the incident light before it reaches the screen; this reduces the required luminance by a factor of 10 or more. When a phosphor with a narrow band emission characteristic is used the filter can similarly have a narrow band to achieve maximum attenuation of incident light with minimum attenuation of emitted light.

For colour displays the situation is further complicated by the lower luminance levels generated by both shadowmask and penetration types of CRT. In both cases, as reported by Brun and Martin (3.1.13), TV raster operation allows contrast ratios of less than two for all colours in a 10^5 lux ambient. However by use of cursive writing it becomes possible to generate displays on a penetration tube having a contrast of 3.5 in the green and 1.7 in the red, values which indicate that the luminance levels of colour CRT displays are near to being practicable for some military aircraft applications.

The contrast required for any particular display depends upon the characteristics of the displayed information and particularly upon whether the format is symbolic or pictorial. Colour displays generally require less brightness contrast because they impart information via colour contrast. Head-up displays create unique problems because the symbology is perceived against a real-world background; making allowances for the optical characteristics of the combiner, the required symbology luminance is approximately equal to that of the real-world scene.

3.1.6.3 Colour

The colour of light emitted is determined by the phosphor used on the screen and a considerable number of phosphors have been developed covering most of the visible spectrum. Their characteristics are listed in the JEDEC P number register operated by the US Electronic Industries Association, who have also issued guidelines on phosphor measurement methods. A description of recent development in CRT phosphors has been given by Woodcock and Leyland (3.1.14).

The need for high luminous efficiency has caused most monochrome phosphors for airborne use to be either green or white. Several suitable green phosphors exist, as shown on the colour triangle in Fig. 3.1.5, and efficiencies of better than 50 lm/W are obtainable at low current density. However it should be noted that all phosphors show non-linearities in their characteristics and the high efficiencies obtained at low current densities may fall off unacceptably at higher current levels. For example, the new rare-earth P53 can accept much higher currents than some earlier P1 and P43 phosphors although it is less efficient up to 3000 cd/m^2.

For colour displays it becomes necessary to use phosphors of efficiency significantly lower than the 50 lm/W quoted above, which partly accounts for the brightness problems described in section 3.1.6.2. Shadowmask tubes using three coloured phosphors can reproduce a wide range of colours. Also shown on Fig. 3.1.5 are the characteristics of

P49 which is one of the phosphor mixes used in penetration tubes, and the EHT voltages needed to produce the colours at different points along the straight-line characteristics of the mix.

Colour displays of both the shadowmask and penetration types have the characteristic that, because the emissions from the separate phosphors are added together at the eye, the luminances achievable at the intermediate colours are greater than at the primary phosphor colours.

3.1.6.4 Flicker

This visual characteristic is not perceived at all provided the refresh frequency of the display is kept above a critical value, typically in the range 50-60 Hz but dependent upon the lighting characteristics (3.1.15). If the persistence time of the phosphor is greater than a few milliseconds it can have a useful effect in reducing perceived flicker, although for dynamic displays it is not possible to rely on a long persistence phosphor as this will result in 'smearing'.

Care must be taken if the display is used in a vibrating environment, since with short persistence phosphors it is possible to produce an aliasing effect due to the interaction of the refresh frequency and the vibration frequency. Short persistence phosphors also create problems when used in head-up displays incorporating cameras, and synchronisation of the camera with the display scan becomes necessary.

Particular care has to be taken to match the persistence characteristics of the phosphors used in colour tubes when these are viewed in a vibration environment, otherwise a 'colour break-up' may be perceived by the observer.

3.1.7 STATE OF DEVELOPMENT

The cathode ray tube is by far the best known and most widely used electronic display device, and its technical development is well established and mature. Nevertheless the particular problems associated with its use as an airborne display have resulted in a number of on-going developments intended to improve its overall performance.

Monochrome tubes are now available and in widespread use, and these generally meet most airborne requirements (3.1.16). They are typically used in cursive mode for head-up displays for daytime use, and in either raster mode or cursive mode for head-up displays in night use and for head-down panel displays. The desire for head-up display of pictorial information from FLIR sensors has led to the development of CRTs which can operate at high performance in both raster and cursive modes.

Other current developments in monochrome tubes are aimed principally at improving the contrast ratio and MTF under high ambient brightness conditions; these improvements are being achieved through narrower beam widths from better guns, improved electron optics and better phosphors. The dispenser cathode (3.1.17) is able to provide a higher beam current density; it is usually made of a porous matrix of osmium/tungsten which allows electron emitting material to be drawn from beneath the surface, and because it can be manufactured to a precise shape allows the beam to be very accurately positioned within the electron optics. Care has to be taken to prevent the cathode from being poisoned by residual gas molecules, and the complications which this produces in the CRT production process have meant that tubes employing dispenser cathodes are only recently emerging from the development phase. Particular care must also be taken with the thermal design because of the considerable heating at the electron gun.

As for electron optics, the principal improvement here is that more sophisticated focus compensation can now be generated electronically using relatively cheap integrated circuit techniques.

Considerable improvements have been made in the phosphors in recent years (3.1.14), and narrow-band rare-earth activated phosphors are becoming more common. Their principal advantages are their better match with narrow-band filters intended to increase contrast and their use in combination with diffractive optic elements in head-up displays. Another interesting development is the new P53 phosphor which can accept much higher current densities than previous phosphors without saturation or damage and is therefore well suited to be used with dispenser cathodes in the next generation of tubes. Another area of phosphor development of considerable potential importance for airborne CRTs is that of transparent thin-film phosphors which would significantly reduce the back-scatter of ambient light. Only limited progress has so far been made, principally because of reduced efficiency due to light-trapping in the phosphor, decomposition at high beam currents and chemical poisoning problems.

Colour CRTs have only recently been adopted for airborne use, initially for display of weather radar information on general aviation aircraft but more recently they have been chosen for a range of head-down displays on large civil aircraft such as the Boeing 757 and 767 and the Airbus Industrie A310. In these cases shadowmask tubes have been used, for weather radar in a raster mode but for the large civil aircraft applications cursive writing has generally been chosen. The brightness/contrast limitations described in section 3.1.6.2 are acceptable for the lighting conditions in this class of aircraft and careful packaging and internal design have apparently reduced the vibration problems to acceptable levels. Limited use has also been made of penetration tubes in head-up displays intended as landing aids for civil aircraft.

The difficulties in designing colour tubes to provide a satisfactory visual display under military aircraft environmental conditions have been described in section 3.1.6 above, and the mechanical aspects were referred to in section 3.1.2. Thus far the applications of colour tubes in military aircraft have been restricted to limited use of high brightness penetration tubes for daytime operation. It may be predicted that the improvements in phosphors, cathodes and electron optical design already described for monochrome tubes will also be applied to penetration colour tubes to allow their increasing use in military aircraft in the future. However it appears unlikely that when driven in raster mode the brightness and contrast will be adequate for daylight use, so that the display of high resolution colour pictorial information by this technique does not appear likely in the medium term.

One interesting possibility for the use of penetration tubes in aircraft takes advantage of a dual-monochrome mode of operation. Thus high-brightness green would be used for daylight operation, and low-brightness red or amber at night with the benefit of low detectability and good adaptation to scotopic vision.

As indicated in section 3.1.2.2, recent developments in the design of shadowmask CRTs suggest that these may soon be sufficiently rugged for application to military aircraft.

3.1.8 SPECIAL CRTs

In view of the widespread use of CRTs it is not surprising that attempts have been made to find alternatives to the conventional monochrome and colour types already described. Although none of them appear likely to be competitive with conventional CRTs for airborne use in the short or medium term, three types are briefly mentioned below which could in the longer term have some application. No description is given here of the various forms of storage tube which have been developed, since it appears that with the advent of inexpensive solid-state digital stores in digital data processing, the need to use airborne displays with built-in storage has largely disappeared. However, it may be noted that storage tube techniques can be used to achieve extremely high brightness thanks to the continuous 'flood' of electrons impinging onto the phosphor screen. It may also be mentioned that dual-gun penetration multi-colour storage CRTs have been produced on an experimental basis by Thomson-CSF.

3.1.8.1 Flat CRTs

A flat thin CRT was described by Aiken (3.1.18). The gun emits an electron beam parallel to the face of the phosphor screen, and the beam is deflected by separate horizontal and vertical electrostatic deflection plates before striking the screen. In each case the beam is deflected through 90°, the beam position and thus the spot position being controlled by the deflection plate potential. The main problem with this type of tube concerns poor focus and geometrical distortion, but as with conventional tubes, LSI circuitry offers the possibility of correcting some of the deficiencies in electron-optic performance and may lead to acceptable pictorial quality. Sinclair in the UK have described a similar type of tube in a miniature portable TV to be marketed in 1982 (3.1.19); this has dimensions of 100 × 50 × 20 mm, and the phosphor screen on the rear of the tube is viewed through a Fresnel lens incorporated into the front glass screen, as shown in Fig. 3.1.6.

3.1.8.2 Digitally-addressed CRTs

The combination of digital addressing with the high luminous efficiency of cathodoluminescent phosphors appears potentially attractive for airborne use. The most extensive development programme of a tube using such techniques was that of the Northrop Corporation, under the name 'Digisplay', and has been described by Goede (3.1.20). Instead of a single scanning electron beam, the Digisplay uses a large number of individual beams, each striking the phosphor layer at a fixed spot. Addressing is carried out by controlling the average intensity of the individual beams, using a series of aperture plates interposed between the large area cathode and the phosphor screen. Patterns of conducting material around the apertures can be digitally addressed with 30 V potentials so that any individual electron beam can be switched on or off.

Several versions of the display are described by Goede of which the most useful for airborne use is a 512 character display using 7 × 5 fonts on a 135 mm × 95 mm active area, with an average spot brightness of 820 cd m^{-2}. A colour version was also made but the development programme was subsequently stopped and no other tubes of this type are currently available except for the Character Display Tubes from EEV(UK) which show only a single 7 × 5 font character. It appears that the problem of matrix addressing while maintaining high brightness will require the use of latching circuits which have not so far been developed in a form suitable for this type of tube.

3.1.8.3 Dark trace tubes

Certain materials have the property that when struck by an electron beam they develop absorption bands in the visible wavelengths. If such materials are used in CRTs instead of phosphors, it becomes possible to write a dark line instead of an emissive line, and a CRT using this principle could be useful for airborne use although it would need separate illumination as with a conventional electromechanical instrument. Practical difficulties have so far prevented the development of viable tubes of this type; these are mainly concerned with the slow writing speed necessary with these materials (typically 2 m/s) and the need to erase at a similar speed.

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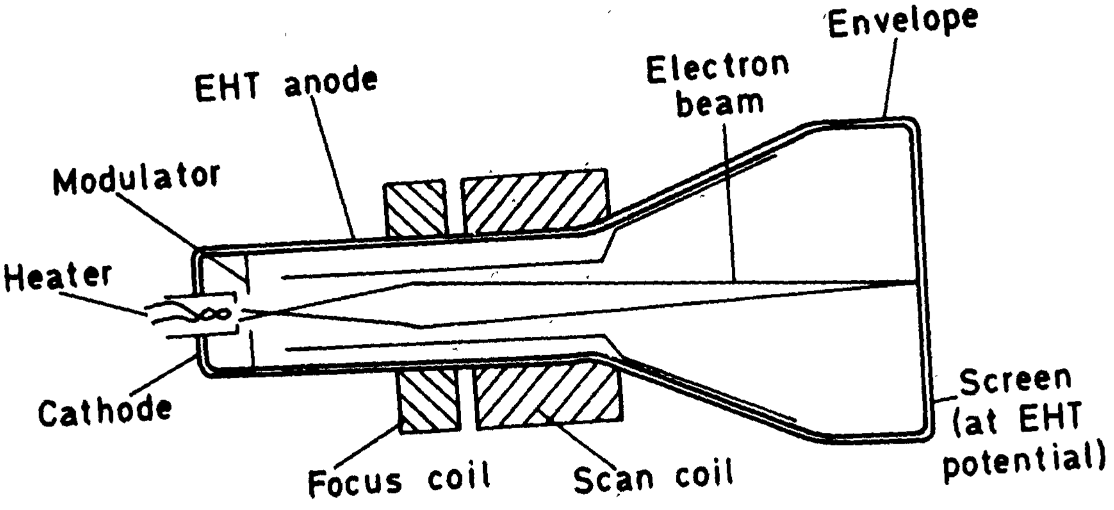
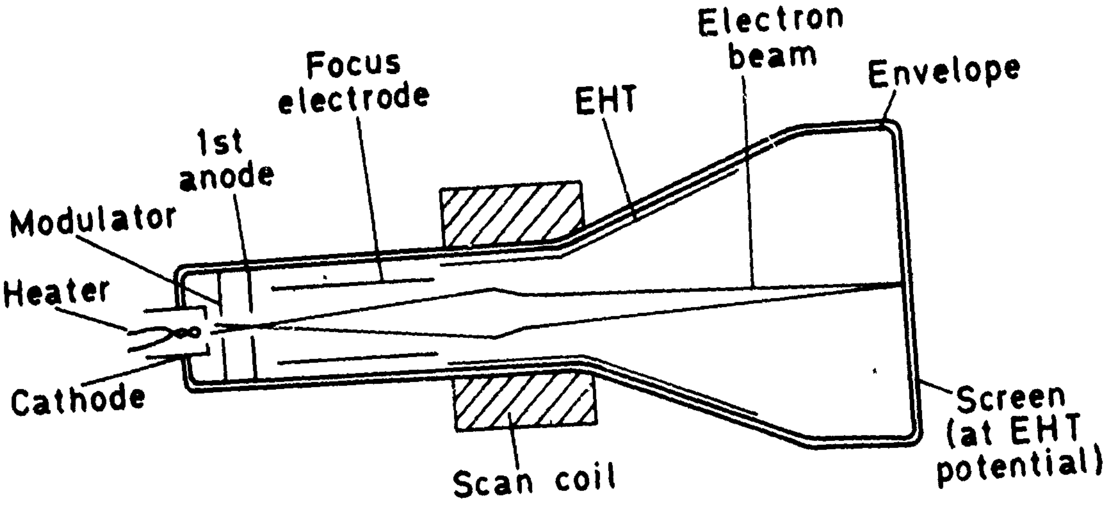


Magnetic focus tube



Electrostatic focus tube

Fig. 3.1.1 Monochrome CRTs.

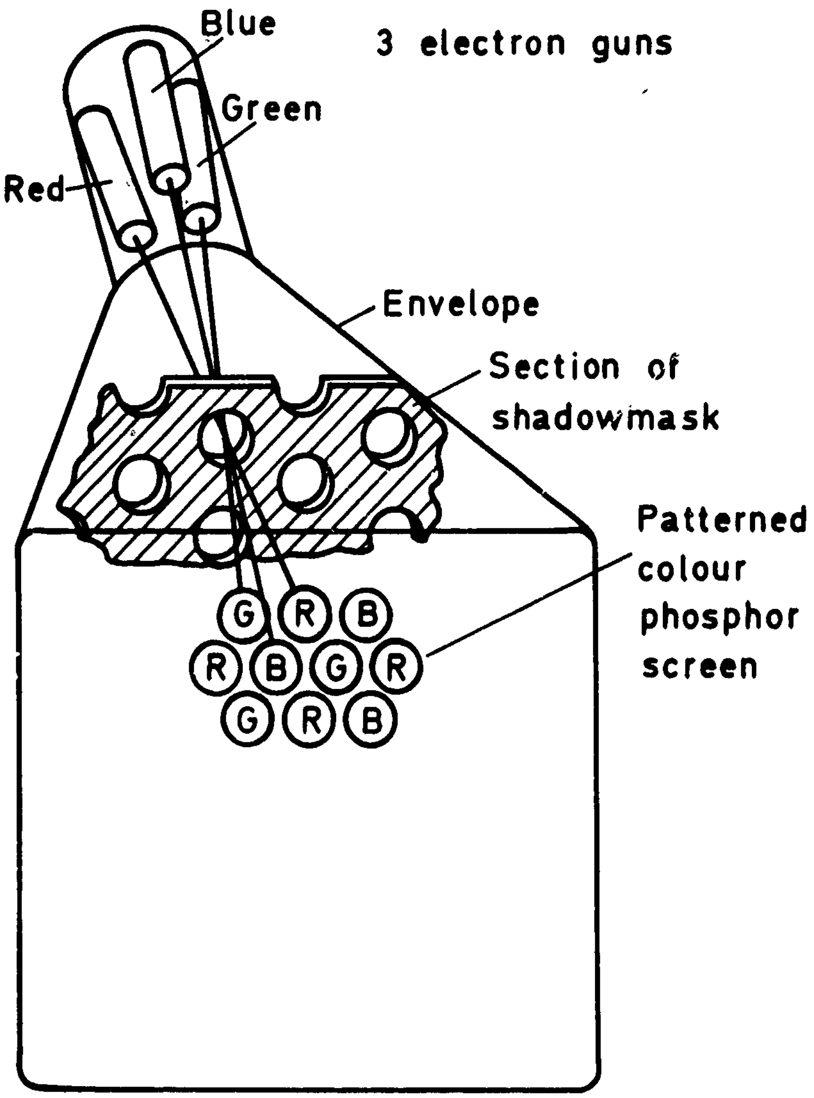


Fig. 3.1.2 Shadowmask CRT.

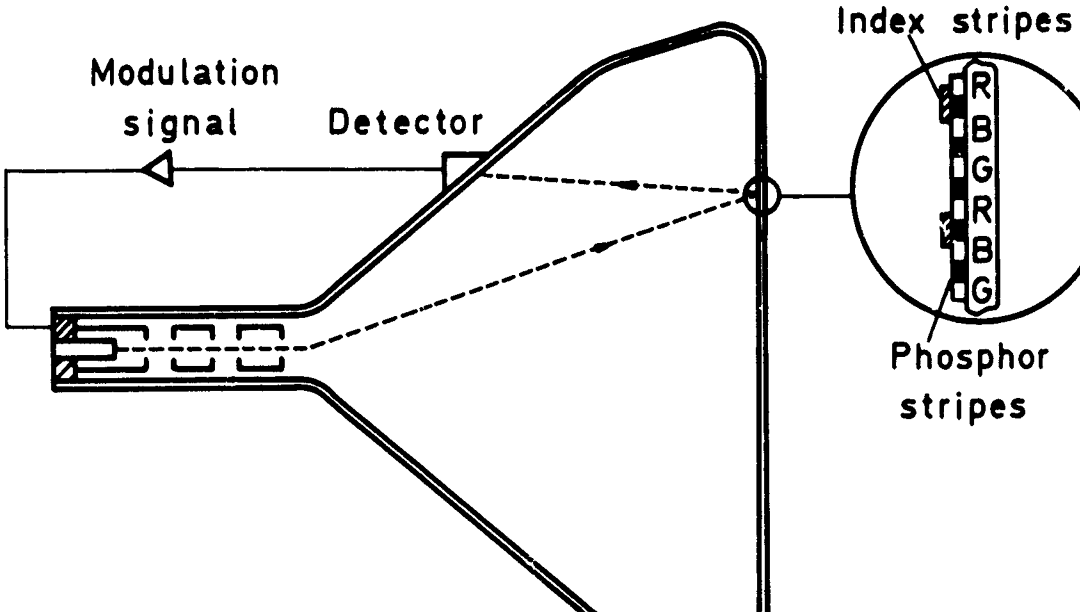


Fig. 3.1.3 Beam - index CRT.

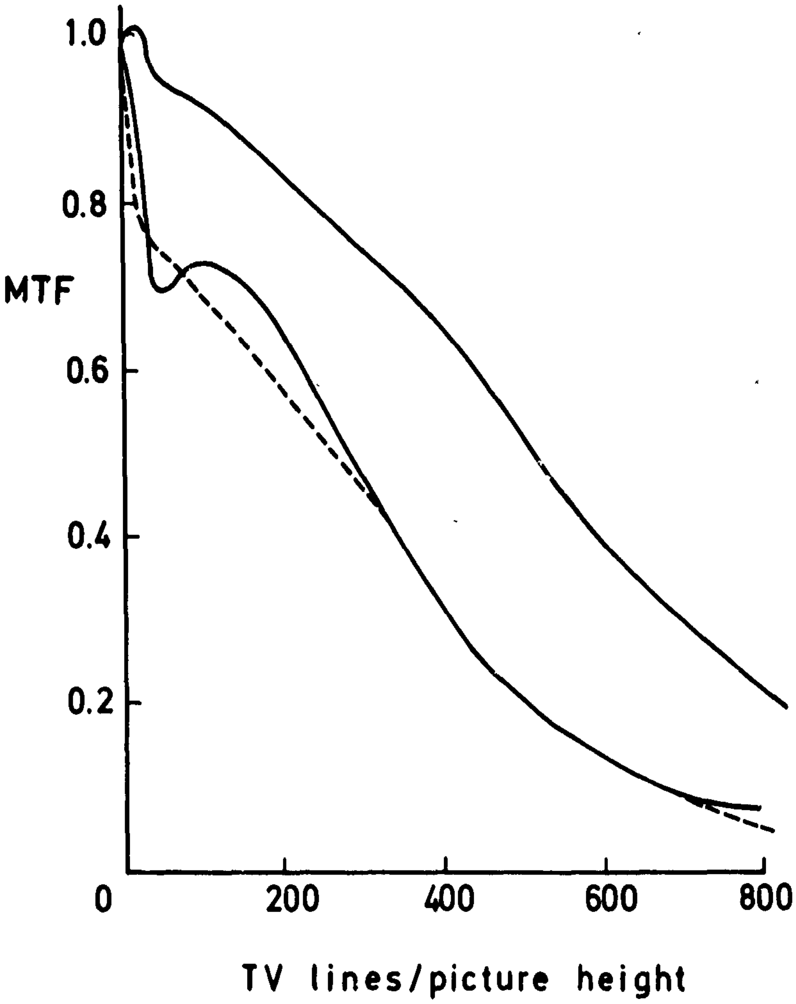


Fig. 3.1.4 Typical CRT modulation transfer function curves.

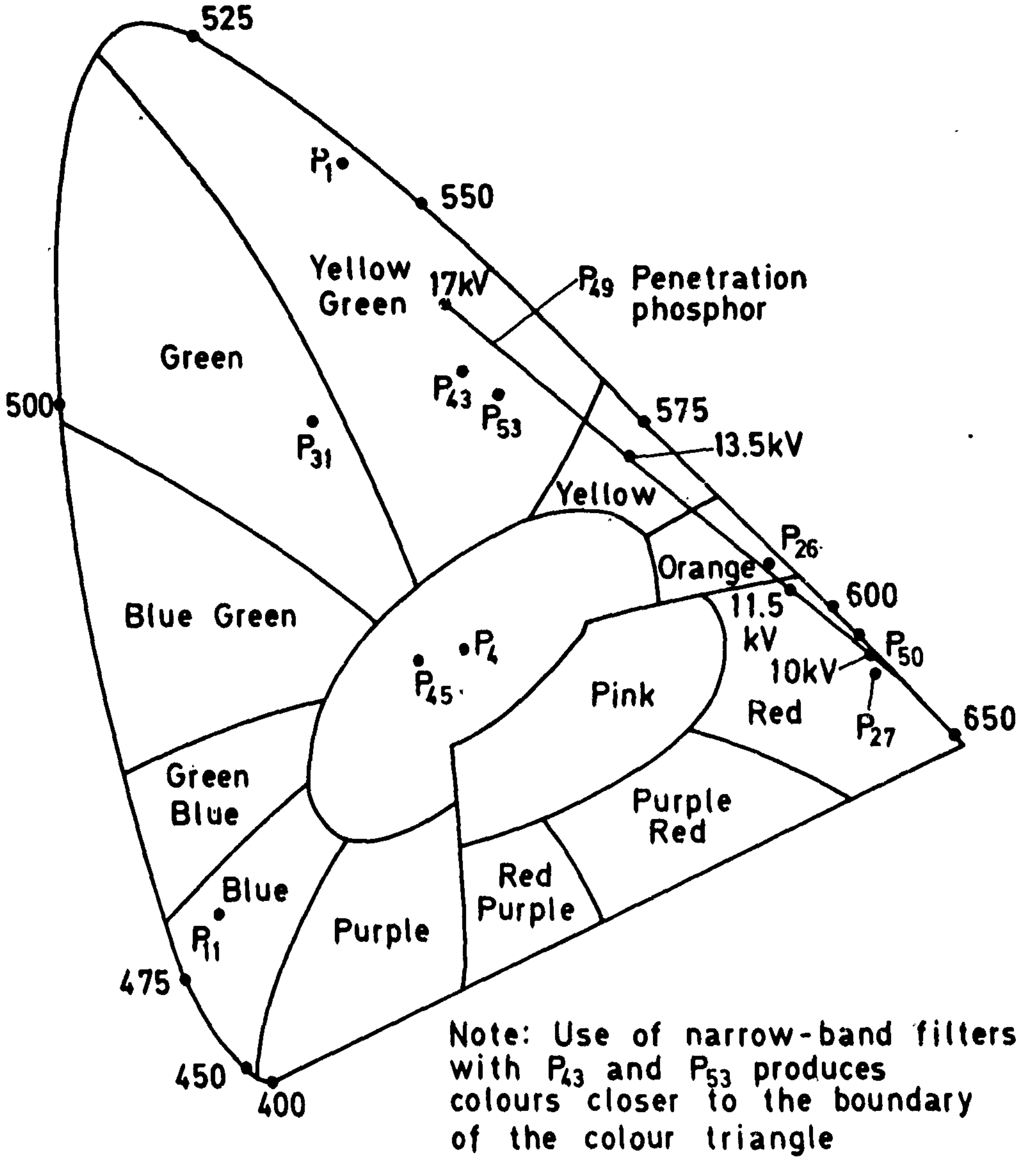


Fig. 3.1.5 CRT phosphor coordinates.

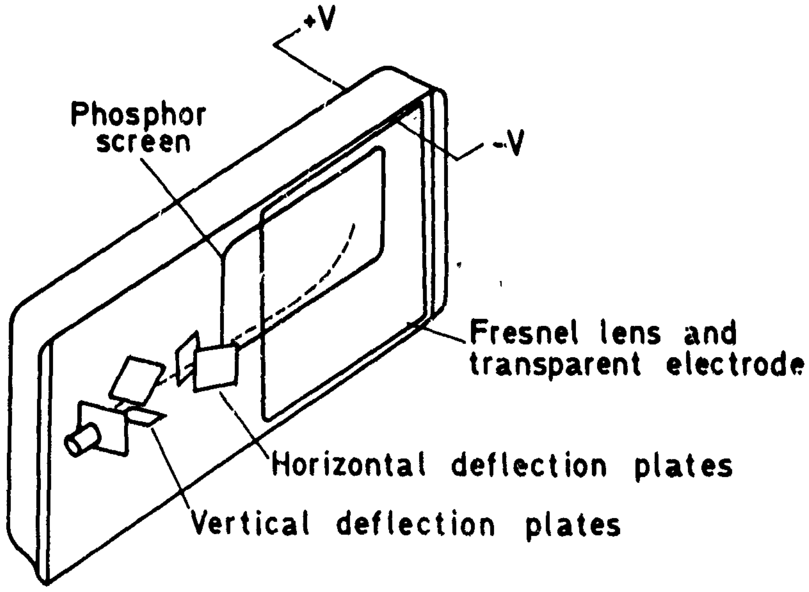


Fig. 3.1.6 Sinclair flat CRT.

3.2 VACUUM-FLUORESCENT TUBES

3.2.1 HISTORICAL SURVEY

The vacuum-fluorescent tube was first marketed as a display device in 1967, and its subsequent history is described in Ref. 3.2.1. The first generation of these displays mainly comprised individual tubes, each capable of displaying one 7-bar numeric, and these were extensively used in desk-top calculators. From 1971 onwards tubes became available capable of displaying up to twelve numerals within a single flat glass envelope, and in further improvements from 1974 onwards the construction was simplified by the replacement of ceramic anode substrates by glass substrates forming a part of the vacuum envelope. Subsequent developments have been concerned with improving the colour characteristics and efficiency of the phosphor, with the use of thin film printing in the production process, and with expansion of the number of elements in each display so that matrix displays of up to 250 × 250 elements are now available. The most recent advances are aimed at improving the luminance of large area displays by the use of active substrates; this allows more rapid addressing, and compatibility with TV display formats.

3.2.2 PRINCIPLES OF OPERATION

Vacuum-fluorescent tubes form a type of display in which light is emitted from phosphor-coated anodes when these are subjected to electron bombardment, using the principle of cathodo-luminescence. As compared with cathode-ray tubes the electron energies are much lower, typically no more than 50 eV, and the display pattern is formed of discrete anode elements rather than by a focussed beam striking one part of a continuous anode surface.

Fig. 3.2.1 shows a typical layout for a simple tube. Although diode operation is possible, tubes are usually constructed as triodes to allow easier control of luminance. The cathode is a thin tungsten filament which is run at dull-red heat and is therefore not normally visible, and the grid is a thin metallic mesh. The anode is normally formed of a pattern of thin-film electrodes deposited onto the top surface of the rear glass wall of the vacuum envelope, and on each of the electrode elements a further deposit of phosphor is laid down. This fixed pattern of anode/phosphor elements may be in the form of a series of 7-bar numerals, 5 × 7 dot-matrix patterns, or sometimes a series of bars forming an analogue thermometer-scale indicator. The simpler types have been described by Suzuki (3.2.2) and Sato (3.2.3), and a large display of 240 characters each formed of a 5 × 7 dot-matrix by Kasano *et al* (3.2.4). A recent paper by Uemura and Kiyozumi (3.2.5) describes an experimental vacuum-fluorescent TV display in the form of a 241 × 246 element array with full addressing flexibility at TV frequencies. This incorporates active elements on a silicon substrate to isolate the tube pixels from the address circuits, and the display is thus constrained to the substrate size of $23 \times 23\ \text{mm}^2$.

The luminance of each dot or bar is controlled by a combination of the grid and anode voltages; in practice it has been found desirable to operate the grid and anode at the same potential to avoid focussing problems, so the control of electron current and luminance in each area of phosphor is through simultaneous variation of grid and anode voltage. For the smaller matrix tubes the grid voltages of the individual pixels are operated in a time-multiplex mode; duty factors of 1/20 to 1/50 are typical for these displays. For the TV display the loss of luminance resulting from time-multiplexing is obviated by the use of capacitances at the individual anodes which maintain current throughout the duty cycle.

3.2.3 PHYSICAL CHARACTERISTICS

A typical simple tube consists of a flat-walled glass envelope as shown in Fig. 3.2.1. The dimensions of the rectangular flat front and back are determined by the particular array of numerals or the matrix size and shape, and also by the application which may be for a series of small numerals on a pocket calculator, or may be much larger as on consumer products such as clocks, washing machines, etc. Character sizes range from 5 mm to 15 mm in height, and overall display sizes from 20 mm × 50 mm to 140 mm × 270 mm. Typical display thickness is in the range 10 mm to 14 mm.

The matrix TV display has 241 × 246 picture elements and a picture size of 23 mm × 23 mm. This is clearly too small for most practical applications, and to fabricate a direct-view display it will be necessary to mount several silicon substrates together to form a single continuous display. It is indicated in Ref. 3.2.5 that such a joining process may be possible.

The display devices are very rugged and can withstand a broad range of environmental conditions; they are therefore suitable for a wide range of industrial and consumer applications, and using well-established vacuum-tube technology there are few difficulties in their production. The production process was greatly simplified and reliability improved in 1974 when thick-film printing techniques on a glass substrate were utilised to replace ceramic substrates, and allowed a greater variety of display patterns to be produced. An example of this is provided by the 240-character display described in Ref. 3.2.4 in which to improve production yield and reliability it was decided to minimise the number of electrical overlapping points in the anode-matrix wiring array. Ref. 3.2.4 describes the production process which produced a 3-layer anode substrate having only two overlapping points per dot. Ref. 3.2.5 describes the production process for the experimental TV display.

3.2.4 ADDRESSING/DRIVING AND SYSTEM INTERFACE

Except for very simple single-numeral displays, individual dots or bars are excited by time-multiplexing. Ref. 3.2.4 describes the method used for a 240 character display, each character being formed by a 7 × 5 dot matrix plus a cursor; this is the most complex display which is commercially available but the addressing technique used on simpler displays is similar in principle.

The 240 characters are divided into six lines of 40 characters, with 40 grids each covering a column of six characters. The anodes for each column have 216 individually connected dots (six characters × 36 dots). Complete freedom for addressing individual dots is provided by time-multiplexing the voltages on the 40 grids; allowing for a blanking time of about 50 μs between grid pulses a duty cycle of 1/45 is obtainable when the complete cycle is repeated at 50 Hz.

A microprocessor is used for the addressing system. The CPU executes control of driving circuits and I/O data, and the driving program and all character patterns are stored in ROM. A shift-register is used to assemble a column of six characters before these are input to the drivers, allowing the pattern for one column to be built up while the previous column is being excited. Anode and grid voltages have a maximum value of 50 V, the luminance of the display being reasonably linear with voltage. Anode and grid currents per column are in the 0-30 mA range, so that the driver circuit requirements are compatible with IC characteristics. A single IC package incorporating shift registers, latches and drivers is described in Ref. 3.2.4.

The TV matrix display uses a MOSFET array formed on the silicon substrate to isolate the pixels from the matrix addressing array. Each pixel has a phosphor anode which, as shown in Fig. 3.2.2, is deposited as a layer on the drain of a p-channel-type MOSFET transistor. The picture element is selected for energising by the applied voltages on the gate and source, which are matrix-addressed, and a potential corresponding to the source voltage is produced at the phosphor layer. By building in capacitance between the drain electrode and the silicon substrate the voltage on the phosphor decays slowly when the applied matrix voltages are cut off, so reducing the luminance reduction which is otherwise inherent in matrix addressing. Ref. 3.2.1 mentions that studies are in progress on the application of TFT substrates to vacuum-fluorescent tubes; these would similarly allow higher brightness to be achieved.

3.2.5 VISUAL CHARACTERISTICS

The patterns of figures or lines which can be displayed are defined by the shapes of the phosphor layer printed onto the anode, and usually take the form of 7 × 5 dot matrix or 7-bar numerals which are similar in size to other displays such as LCs and LEDs.

The principal visual characteristics of interest are the light emission from the phosphor and the reflection characteristics. The phosphor normally used is ZnO-Zn which has a broad-band emission peaking near 0.5 μm, and having a half-peak width of about 0.1 μm. A range of individual colours from blue to orange can be obtained by using suitable filters. However, the use of filters decreases the perceived luminance which typically has a maximum of 700 cd m^{-2} when unfiltered, but only 200-300 cd m^{-2} if filtered to produce a green colour. The use of filters does improve contrast by reducing the level of light scattered back from the interior surfaces of the display; the worst effect of this scattered light is caused by the printed phosphor patterns on the anodes, the grids and the individual conducting leads to the anodes which all contribute to a fixed pattern which is very apparent in bright ambient illumination. The use of narrow-band filters as in some CRT displays to minimise ambient light scattering is not feasible with vacuum-fluorescent tubes because of the broad-band emission from the zinc oxide phosphor.

Alternative phosphors of different colours are being developed, but it appears that at the low voltages used in this type of display their luminous efficiency is likely to remain less than 5 lm/W.

3.2.6 STATE OF DEVELOPMENT

The vacuum-fluorescent tube is in large-scale production for a range of display applications including calculators, radio and communication equipment, clocks and other domestic and industrial appliances. The development of the 240-character display indicates that further market penetration into computer terminals and word processors may be possible. However, the use of separate filament cathodes and grids may limit the extent to which large matrix displays can be realised as production devices.

Excellent reliability, life and environmental characteristics are claimed, and production cost is generally relatively low. For these reasons the display is potentially attractive to the automobile market, although the difficulties of viewing the display in bright ambient conditions may limit this application. Ref. 3.2.5, in describing the experimental work associated with the TV matrix display, quotes luminance levels of around 15000 cd m^{-2} for individual pixels fabricated with transistors and capacitors and operated at TV refresh frequencies. If such values can be achieved with representative displays then they should be capable of widespread use in aircraft cockpits, but thermal problems inherent in such a display will be very difficult to solve, and it is likely that much further work will be necessary to achieve these high levels of luminance in production displays.

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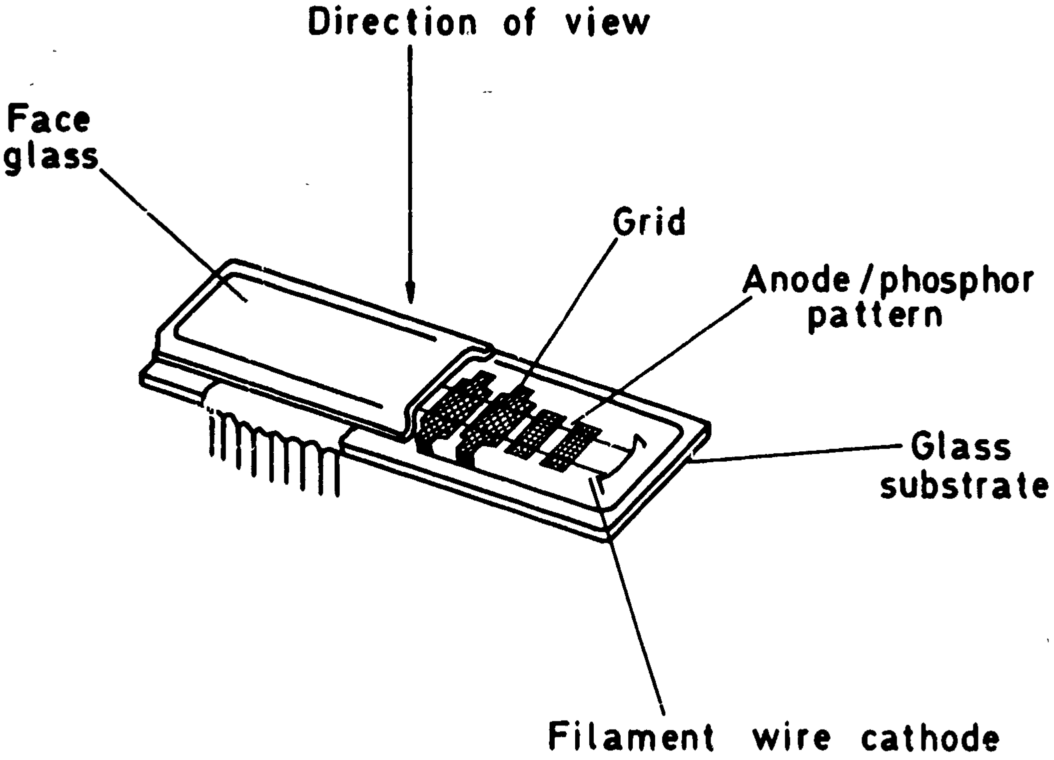

Fig. 3.2.1 Vacuum - fluorescent tube cut-away view.

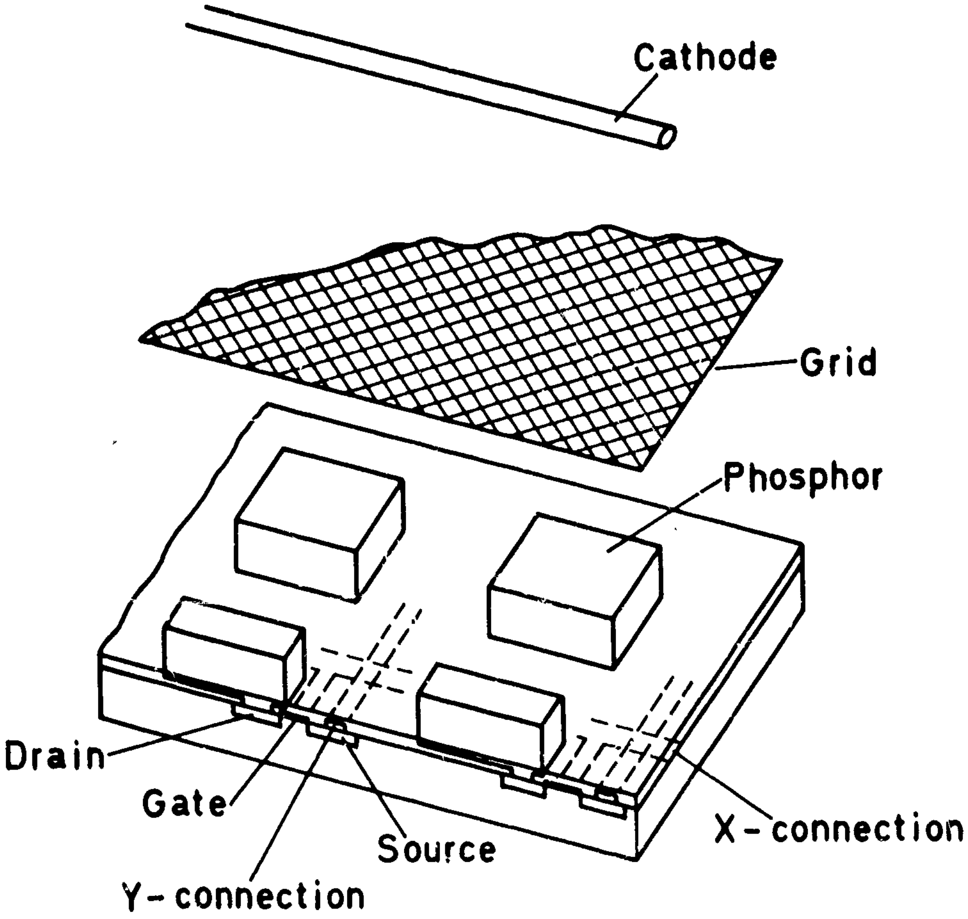

Fig. 3.2.2 Vacuum fluorescent matrix display with MOSFER substrate.

3.3 LIQUID CRYSTAL DISPLAYS

3.3.1 HISTORICAL SURVEY

The term "Liquid Crystals" first used by Lehmann in 1890, is applied to substances whose rheological behavior is similar to fluids, but whose optical behavior is similar to the crystalline state over a given temperature range. It designates a state of matter that is intermediate between solid crystalline and ordinary isotropic liquid phases. Liquid crystals flow like ordinary liquids, i.e., they adopt the shape of their container. On the other hand, they exhibit anisotropic properties as do solid crystals. One therefore can define liquid crystals as "condensed fluid phases with spontaneous anisotropy" (3.3.1). Liquid crystal phases are also called mesophases or mesomorphic phases because of their intermediate nature.

The discoverer, Reinitzer (3.3.2), provided the first detailed description of the nature of liquid crystals in 1888. Lehmann (3.3.1) also reported on detailed observations of liquid crystal or mesomorphic behavior. Others who provided new understanding included Born and Vorlander (3.3.3 & 4). Following the nomenclature, originally proposed by Friedel (3.3.5), thermotropic liquid crystals are now classified into three types: nematic, cholesteric and smectic. Recent work was initiated by Fergason and Heilmeier and associates (3.3.6 & 3.3.7) who pointed out the importance of liquid crystals for thermographic and electro-optic applications.

Many thousands of organic compounds form liquid crystals when the solid crystal is heated above its melting point. The mesomorphic phase appears as a more or less viscous fluid which can be identified visually by its characteristic turbidity or with a polarizing microscope and by its optical birefringence. At higher temperatures, transitions to other mesophases may occur in some phases, while other compounds display only one mesophase. In either case, at another well defined, higher transition temperature, the turbidity suddenly vanishes, giving way to the ordinary liquid. This phase change is reversible and of the first order with a latent heat of some 100 cal/mole.

A LCD in its simplest form consists of two glass plates coated on their inner surface with an electrode layer, between which a liquid crystal layer about 12 m thick is sandwiched. A voltage applied to those electrodes produces an electric field that affects the LC. The electrode layer can be homogeneous or a pattern can be etched into it so that by driving the appropriate elements various "pictures" can be created. To observe the electro-optic effects of the LC layer, at least one of the electrode plates must be transparent. If operated in a transmissive mode, both electrodes must be transparent. For reflective mode operation, an external reflector or the back electrode may be a suitable reflecting layer. In essence, while most liquid crystal displays operate as reflective devices, returning a portion of the ambient light to the viewer's eye, they may also be fabricated from transparent materials and used in a transmissive mode. An integral light source may be used with either mode of operation. Applications range from digital watches to large screen projection systems with color images. Liquid Crystal displays have several characteristic advantages. They operate at low voltages, typically in the range of 2 to 20 volts, thus being compatible with semiconductor drive circuitry. This also allows low power operation, typically 0.05 to 0.5 microwatts per cm Most system requirements, which may require a light source and/or heating, would still result in relatively low power operation for most applications. Due to the reflective nature of liquid crystal displays, legibility generally increases with increased ambient lighting. This good viewability is achievable in direct sunlight conditions (typically 8-10 shades of grey). Tests to date and basic failure mechanism analyses indicate high reliabilities and lifetimes of 20,000 hours or more for liquid crystal displays of 30,000 pixels. There are disadvantages as well. Liquid crystal displays often require external lighting, since the display itself only performs the function of light modulation. In addition, since the liquid crystal phase exists over a limited temperature range, typically 100°C, around room temperature, existing LC materials cannot meet the full operating temperature range for military equipment (-55°C to +85°C) without temperature compensation. Another handicap is that, at low temperature, the LCDs are generally very slow (≈1 sec). Materials improvements currently underway should result in LC displays with improved temperature and response characteristics. For example, these drawbacks have been mitigated by those developments which employ smectic materials (see 3.3.2.9). LC displays can be matrix addressed to a limited degree, but in many cases require active element addressing circuitry, e.g. MOS FET, or Varistor devices and capacitors for each display element.

Commercial developments have concentrated on numeric displays, with liquid crystals displacing LEDs in the current watch and calculator markets because of their lower power consumption and lower cost. For military applications, government sponsored efforts have mainly concentrated on the development of "video" displays for presentation of sensor imagery and for graphics and alphanumerics. Optical projection and fiber optics magnification techniques are currently being developed in order to combine the images of four or more LC displays to provide increased resolution and larger display areas. In spite of the success of LCDs in low complexity displays for the consumer and industrial markets, there are many aspects which must be carefully considered where LCDs can be expected to be employed in military environments. An excellent overview of liquid crystals and applications is Meier et al (3.3.8); for further in-depth examination of liquid crystal materials, see Saeva and Chandrasekhar (3.3.9 & 3.3.10).

3.3.2 PRINCIPLES OF OPERATION

3.3.2.1 General

Liquid crystals are composed of elongated, rod-shaped organic molecules having a length to width ratio of 3 or more. The distinguishing feature of the liquid crystalline state is the way in which the molecules are spatially arranged. In a perfect crystalline solid, the relative positions and orientations of the molecules are well defined, whereas in a liquid, the relative positions and orientations are virtually random. In a liquid crystal, however, the relative orientation of the molecules remains well defined, but various aspects of the positional ordering of the crystal are lost, as shown in Fig. 3.3.1. Organic liquid crystals may be classified as nematic, smectic, or cholesteric. These states are similar in that they exist in a state between a fully crystallized solid state and an isotropic liquid and differ in the extent of the lattice order preserved. In a nematic liquid crystal, all positional order is lost, only the orientational order remaining, i.e., the molecules are able to translate in any direction to their immediate neighboring molecules but are constrained to be parallel. In a smectic material, of which there are several types, the molecules are also constrained to be parallel in layers but are randomly positioned within the layers. Cholesteric materials, closely related to nematics, have a small angular twist between molecules which results in a spiral or helical structure of well defined pitch. Nevertheless, nematic and cholesteric liquid crystals are clearly liquid, flowing readily with quite low viscosity, while smectics generally have very high viscosity. Consequently, the orientational order of the molecules is not preserved automatically over infinite distances as in a solid crystal, but exists typically over distances up to about a millimeter. Figure 3.3.1 illustrates the phase diagram of a hypothetical liquid crystal, showing the nematic, smectic, and cholesteric phases. In real materials, the number of distinct smectic phases may be different, while the nematic phase may be absent or replaced by a cholesteric phase.

An important concept is that of the "director" which describes the principal alignment direction of the molecules; in essence, the optical axis. It does not refer to the orientation of an individual molecule, since that is subject to thermal fluctuations; instead, it refers to the average orientation of a group of molecules.

A very significant aspect of liquid crystals is the large anisotropy of most of their physical properties when measured in directions parallel and perpendicular to the director. For example, the anisotropy of dielectric constant means that electric fields can be used to control the orientation of the director. This effect is utilized in all the displays to be discussed. This dielectric anisotropy may be either "positive" (i.e., maximum dielectric constant parallel to the director) or "negative", and both types of material have been exploited in displays.

Liquid crystal materials may also interact strongly with solid surfaces. These effects are also important since, in the absence of an electric or magnetic field, the structure and orientation of thin layers of liquid crystal are largely determined by surface interaction. Methods have been developed for treating glass surfaces with organic or inorganic films, possibly followed by controlled mechanical abrasion, which aligns the director either perpendicular to the surface ("homeotropic" alignment), or parallel to the surface ("homogeneous" or "planar" alignment) or at some intermediate angle. This control of alignment, via surface forces, permits very large areas of uniform orientation and texture to be produced, another important factor for the uniform appearance of displays.

A large number of distinct electro-optical effects have been demonstrated in liquid crystals. These include various scattering effects, interactions with polarized light to produce either variable color or monochrome contrast, birefringence, absorption in dissolved dyes, etc. All of these effects involve molecular realignment caused by the interaction between the applied electric field and the dielectric anisotropy of the liquid crystal. Furthermore, over a wide range of drive conditions it is found that the response of the liquid crystal is determined by the root mean square (RMS) of the applied waveform, rather than by the peak amplitude. Drive waveforms are normally constrained to be ac since, although liquid crystals respond to dc, the presence of dc gives rise to various electrochemical reactions which may rapidly degrade the display.

Figure 3.3.2 shows two flat glass substrates which are separated by a uniform space, typically between 5µm and 20µm thick, which is filled with the liquid crystal. The inner walls of the glass are covered by the electrode patterns which define the active areas of the display. In transmissive cells, both electrode layers are made of a transparent conductor such as an indium tin oxide mixture, whereas in some reflective cells the rear set of electrodes may be metallic. Covering the electrodes are insulator layers of sufficient thickness to protect the liquid crystal from inadvertent exposure to dc. The insulators are coated with alignment layers, if needed. The spacing of the cell is often controlled by a spacer around the periphery though better spacing control is sometimes obtained using inconspicuous spacers distributed over the whole area. The cell is sealed around the edge by either a thermoplastic bond or a higher temperature, more hermetic, glass-frit technique. The polarizers and reflectors required by some display effects are attached to the outside of the glass.

3.3.2.2 Dynamic Scattering (DS) Effect

Historically, this effect was the first to be used commercially, but did not give a fair indication of the potential of LCDs (3.3.11). The effect uses a nematic material of negative dielectric anisotropy containing a dopant to increase its conductivity. Homogeneous alignment layers ensure that clear transmission occurs in the undriven (off) state. An applied electric field produces both current flow and a torque on the molecules. When a critical threshold field is exceeded, a turbulent flow condition occurs. In this state, the director alignment is lost and spatial variations of refractive index occur on a scale suitable for strong light scattering. The (on) state appears cloudy, and when used in the reflection mode, the achievable contrast ratio is rather poor. This effect was soon replaced in most commercial applications by the twisted nematic effect (Section 3.3.2.3), largely because of the better visual contrast, longer life, lower voltage operation, and reduced power consumption of the latter.

3.3.2.3 Twisted Nematic (TN) Effect

A schematic twisted nematic (3.3.12) is shown in Fig. 3.3.3 where a material with positive dielectric anisotropy is used. The diagram of the off-state shows homogeneous alignment on both surfaces of the cell, with these two alignments mutually at right angles. The director then spirals uniformly from one surface to the other giving the 90^0 twist that is used to name the effect. (In practice, various defects in performance are avoided if the surface alignment is not precisely homogeneous; tilt angles of up to 30^0 from the surface being used in some instances, such as that in Fig. 3.3.4, but this does not materially affect the description given here). The front polarizer produces linearly polarized light whose polarization direction is either parallel or perpendicular to the director at that face. Because of the large refractive index anisotropy of the liquid crystal, the plane of polarization is guided through the cell, following the rotation of the director. It thus emerges polarized orthogonally to the incident polarization. If the analyzer is perpendicular to the polarizer, this emerging light is transmitted. When a voltage above the threshold voltage V_T is applied, the director rotates to be parallel to the electric field in all places. No guiding of polarization occurs, so the transmitted light is absorbed by the analyzer, (of course, by rotating the analyzer through 90^0 the opaque and transmitting states are reversed). When the applied voltage is reduced below the threshold value, the surface forces then reestablish the original twisted structure.

The display may be used either in the transmissive mode, with an independent light source illuminating the rear of the display, or it may be used with a suitable reflector fastened to the rear polarizer, to reflect the ambient light. In the latter case, a diffuse reflector, which does not depolarize the light, is required to maximize the display brightness and contrast. One solution to night viewing of reflective TN displays is to use a "transflective" rear reflector, i.e., a reflector that transmits about 10% of incident light. A very weak light source, placed behind this transflector then gives good transmissive mode viewing in the dark, with a smooth transition to reflective mode viewing at higher light levels.

3.3.2.4 Twisted Nematic Displays

For low power portable applications, drive voltage and current is a most significant consideration. Figure 3.3.5 shows the transmission at normal incidence of a TN cell plotted against applied voltage. There is a fairly well defined threshold voltage V_T, normally occurring between 0.8V and 1.5V. The transmission then falls to about 10% by between 1.3V and 2.2V. To achieve good contrast requires a drive at about 2 x V_T, although usable contrast is obtained at slightly lower voltages. Since power dissipation is roughly proportional to the square of the drive voltage, it is clearly beneficial in terms of battery life to operate with low V_T materials. Because batteries are available only at certain voltages, the major consideration may often be to match the required liquid crystal drive voltage to that produced by 2 or 3 cells of a specified battery.

Good liquid crystal materials have high resistivity, $>10^{10}\,\Omega$ cm, so that cells normally present an impedance of $>10^7$ ohms per square cm in parallel with 1000 to 3000 pF per square cm. When driven with low frequency ac, the power dissipation is consequently limited to a few microwatts per square cm.

The appearance of a TN cell driven slightly above threshold is a strong function of the direction from which it is viewed (3.3.13). This arises because the molecules are constrained to rotate in a particular direction in going from the off to the on state. The threshold voltage for the optical effect at oblique incidence is lower than that at normal incidence in one particular viewing quadrant, known as the "low voltage quadrant". From all other directions the threshold is higher. It is therefore most important to obtain the optimum relative positions of display, observer, and illumination. The observer should always view from within the low voltage quadrant. The ambient illumination may throw shadows of the displayed data onto the rear reflector. Usually, these shadows increase the observed contrast, but if the reflector is at a significant distance behind the liquid crystal layer, there may be a disturbing parallax between the data and its shadow. In this case, the intensity of the shadows may be reduced by illuminating from directions well outside the low voltage quadrant.

The threshold voltage, V_T, of most liquid crystals is temperature dependent, so the temperature coefficient dV_T/dT, is a parameter of interest. Typical values range from -0.4 to -1.0% per °C for TN materials. While this effect is not too important for directly driven displays, providing that enough voltage is available to turn the display fully on at the lowest temperature, it is a very significant parameter for multiplexed displays (see section 3.3.4). Perhaps the most striking effect of temperature is on the response speed of the display, determined largely by the viscosity of the material which is almost inevitably a strong function of temperature. Figure 3.3.6 shows the variation of both turn-on and turn-off times for a particular TN display as a function of temperature. It is clear that, while rapid response is possible at room temperature and above, response is very sluggish below 0°C. Increasing the drive voltage speeds up the turn-on time, but, since the turn-off driving force is determined by the surface alignment layer, one is able to affect the turn-off speed only by reducing the viscosity. In principle, one could achieve faster response with a given material by reducing the cell spacing. In practice, however, this also affects many other aspects of cell design and cannot be reduced. Conveniently , there is a class of materials known as "two frequency" materials (discussed in section 3.3.4.3) where this difficulty may be alleviated.

While there are many other less significant effects of temperature on liquid crystal parameters, as for example: resistivity, cell capacitance, refractive indices, etc., no discussion of them will be included here. The remaining effects of temperature relate to the cell. In general, two methods of cell sealing are in commercial use. The first uses a low temperature (about 150°C) thermoplastic bond. While satisfactory for most commercial and industrial applications, it seems unlikely to satisfy the military environment. For the latter, a high temperature (about 500°C) glass frit method which produces a fully hermetic bond capable of withstanding much harsher environments. The TN cell, however, faces the added problem that the adhesion of the polarizers is very liable to degrade in hot, humid conditions unless some form of secondary encapsulation is used.

3.3.2.5 Cholesteric-Nematic Phase Change Effect

In displays using this effect, a modified form of TN, polarizers are not required, the display being switched electrically between transparent and scattering states. The cell is filled with cholesteric material of positive dielectric anisotropy, the cholesteric pitch being a small multiple of the wavelength of light to optimize the scattering effect. When a field above threshold is applied, the positive dielectric anisotropy causes all molecules to align parallel to the field, the cholesteric twist is lost, and the molecular ordering and alignment are similar to the on-state of the twisted nematic cell. Since no polarizers are used, the cell is completely transparent. When the field is removed, the cholesteric twist is rapidly reestablished throughout the bulk of the material. Since there is then no preferred direction for the orientation of the cholesteric spirals, a strongly scattering, quasi-polycrystalline structure results. Surface alignment layers are not essential for this effect, but may be used to stabilize the texture of the scattering state.

Rather than a threshold voltage, this effect has a threshold field which is determined largely by the cholesteric pitch used. It is generally found that cells which give strong optical effects require somewhat higher drive voltages than twisted nematic cells, typically 5-10 V. When used in the reflection mode, this effect does not give very high optical contrast, but quite acceptable contrast can be obtained in transmission. For projection applications, a simple Schlieren arrangement will give excellent contrast. The C-N Phase effect has not been exploited by itself in displays. Instead, it is now being used with dyes as described in 3.3.2.6.

3.3.2.6 Dyed Phase Change (DPC) Effect

This is a direct extension of the above effect which includes dyes, dissolved in the liquid crystal to give optical absorption rather than scattering (3.3.14 & 15). The dye molecules must be highly anisotropic, both physically and optically. They must align accurately with the director of the liquid crystal at all times; this is known as the "Guest Host" effect. Also, they must be "pleochroic"; i.e., their absorption spectrum should depend strongly on the relative orientations of the molecules and the polarization of the light. Ideally, absorption should be zero when the optical polarization is perpendicular to the long molecular axis, and strong when the polarization is parallel to that axis, as shown in Figure 3.3.7.

In the driven (on) state of a DPC cell, all the liquid and dye molecules are forced to align perpendicular to the plane of the cell, so that light passing through the cell is only weakly absorbed. In the undriven (off) state, the twisted cholesteric structure ensures that all polarizations of incident light encounter sufficient dye molecules whose axes are suitably aligned to give strong absorption.

3.3.2.7 Dyed Phase Change Displays

In principle, DPC displays have two major advantages over TN displays. As noted above, they do not require polarizers and therefore appear brighter than TN displays. Secondly, their optical properties are far less anisotropic, i.e., there is no low voltage quadrant - thus they can be viewed clearly over a much greater angular range. The basic cholesteric materials are made by adding small quantities of "twisting" agents to normal, wide temperature range, nematic mixtures. The temperature ranges and viscosities of the resulting mixtures are, therefore, very similar to those of the nematic components.

Choice of the dye component involves many considerations. Its alignment in the liquid crystal host is described in terms of an "order parameter" (3.3.12) which must be as high as possible to minimize absorption in the on state. Its absorption spectrum must be suitable, blue and black being generally preferred. It must be sufficiently soluble in the liquid crystal host to give adequate absorption and contrast without risk of the dissolution of dye molecules at low temperatures. Finally, it must be highly stable when exposed to solar UV radiation. The dyes used in many early investigations (3.3.16) had poor UV stability. It is only recently that dyes combining good stability with high order parameters, good solubility and a wide range of spectra have become generally available.

The overall design and performance of a DPC display, then, is subject to many compromises, since each variable parameter affects more than one of the observable features. A large cell spacing provides good contrast, but at the expense of either slow turn-on or high drive voltage; short cholesteric pitch improves contrast and gives rapid turn-off, again at the expense of high drive voltage; high concentration of dye gives good contrast but reduces on state luminance and may involve low temperature solubility problems. Clearly, the achievable speed, contrast, drive voltage, etc., will depend strongly on the external design constraints. As an example, consider a moderately thin cell driven at about 10V RMS. A high luminance display is possible with 10:1 contrast ratio using a high order parameter dye. Turn-on times of ≃100ms and turn-off times of 20ms are achievable at room temperature, which is much faster than the response of a TN display.

Threshold voltage is affected by temperature in much the same way as that for a TN display. Values of dV_T/dT are of the order of -1% per ^{o}C. Similarly, response times are affected by changes of viscosity with temperature. However, the fundamentally faster response of the DPC effect means that usable response speeds can be retained to much lower temperatures.

As in the previous effect, the electric threshold is field rather than voltage dependent. With a suitably designed diffuse reflector, this effect is visually very attractive. It should be noted that the displayed information appears bright on an absorbing background, the direct inverse of the conventional TN display. In addition, the elimination of polarizers not only gives a considerably bright display but, also, one that is intrinsically more stable in a hot humid environment. Although dyes of adequate performance are generally available, and drive requirements are well understood, displays using this effect have not yet been exploited to any significant extent. This type of display may be the natural successor to the TN display for a wide range of applications.

The angle of view of a reflective DPC display is determined largely by the properties of the diffuse reflector. By control of the surface texture of this reflector, the on-axis luminance of the display may be played off against the wide-angle appearance. Furthermore, since no rear polarizer is required, the rear reflector can be located inside the liquid crystal cell, thus eliminating the shadow parallax problems discussed earlier (3.3.2.4), and further increasing the luminance and contrast of the display. The same technologies for cell sealing used with TN cells can be used with DPC cells. The absence of polarizers, however, means that the DPC cell should be less susceptible to degradation in extreme environments.

3.3.2.8 Birefringent Effects

The large anisotropy in the refractive indices of aligned nematic liquid crystals permits electrical control of birefringent effects (3.3.17). An example is shown in Figure 3.3.8 where a thin layer of planar aligned liquid crystal of positive dielectric anisotropy is placed between parallel polarizers. The incident polarization is set at 45^0 to the director. By direct analogy with birefringence in solid crystals, the transmission may be analyzed in terms of ordinary "o" and extraordinary "e" rays polarized perpendicular and parallel to the director respectively. For certain wavelengths of incident light, the optical path difference between o and e rays through the liquid crystal will be an integral number of wavelengths and the resultant will pass unhindered through the analyzer. For all other wavelengths, the light emerging from the liquid crystal will be elliptically polarized (to greater or lesser extent) and will therefore be partially or even completely absorbed by the analyzer. Thus, in general, the transmitted light will be colored. When an electric field is applied, the director rotates, changing the degree of birefringence and consequently altering the transmitted spectrum. In the limit, for very high fields, the director becomes normal to the plane of the cell and birefringence is reduced to zero. A similar effect is obtained with negative dielectric anisotropy material in a cell with nearly homeotropic surface alignment. With zero applied volts there is no birefringence and therefore no transmission between crossed polars. As the applied voltage is increased, the molecules tilt away from homeotropic and the birefringence rises. Provided this tilt is in a plane at $\approx 45^0$ to the polarization direction, this birefringence results first in increasing transmission of white light, followed by a series of colors at higher fields. these effects are field rather than voltage dependent. To obtain uniform effects over large areas requires extreme skill in constructing cells with flat and parallel faces. Effects of this type have only received a limited amount of attention both alphanumeric displays and electrically controlled filters.

3.3.2.9 Smectic Effect

Although smectic-type liquid crystals were discovered at the same time as the cholesteric and nematic types, and were one of the three classes recognized by Friedel (3.3.5), their development has been slower than that of the nematic types. Whereas nematics aroused a strong interest in 1968 after the discovery by Heilmeier (3.3.11) of the dynamic scattering and the twisted nematic effects, Tani first described an electro-optic effect in a smectic (3.3.29) in 1971. In 1973, Kahn reported the first application of a thermo-optic effect (3.3.48). That was an infra-red laser addressed slide for use in projection. Other laboratories have since developed similar devices and one of the most advanced can display 4000 X 8000 pixels, the highest information content of any type of display including CRTs. By using filters, full color capability has been achieved. In 1978, Hareng et al (3.3.49) described a new type of projection slide which was matrix addressed electronically at T.V. rates. In 1981, the same authors reported on a direct view, matrix-addressed smectic type display (3.3.18).

Smectics have the most orderly structure of all the liquid crystal effects. Not only do the rod-like molecules point in the same direction as the nematics, but are also arranged in a layered structure. The smectic material is a liquid crystal having strong positive dielectric anisotropy. The smectic liquid crystals present several temperature dependent phases. When the material is heated and allowed to cool gradually, four phases occur, in order: isotropic, nematic, smectic, and the solid crystal. See Fig. 3.3.9. The higher order of the smectic phase compared with nematic phase has the following characteristics:

- While an applied electric field has virtually no effect on the smectic phase, it does align the nematic phase.
- When heated to the isotropic phase and subsequently cooled, the liquid crystal returns to the smectic phase, wherein it is macroscopically disordered. In this phase, it strongly diffuses light. However, if an electric field is applied during cooling, it remains oriented as in the nematic phase and is transparent.

This combined thermal and electrical effect in a smectic liquid crystal can be employed in a matrix-addressed flat-screen display, in which the lines are thermally heated resistances and the columns are the transparent electrodes, permitting the application of a video signal voltage. What is particularly notable, is that after cooling, the liquid crystal state (and hence the optical effect, whether transparent or diffused) tends to remain unchanged, with or without an applied field. The storage time is infinite, as long as the temperature of the crystal remains in a zone corresponding to the smectic phase. On the other hand, erasure is instantaneous upon reheating the liquid crystal to the isotropic phase. The basic principle of panel operation thus depends upon successive heating of the lines, one at a time, and panel column addressing without multiplexing, with an infinite memory requiring no refresh. Since the matrix is simple and made up only of crossed wires, relatively high resolution is obtainable.

The instantaneous drive power of each line increases linearly with the length of the line addressed: The higher the number of lines and the shorter the time lapse between writing successive lines, the higher the average power. Consequently, there is limitation of panel dimensions if fast addressing is required.
Although based on a thermal effect, line access time can be relatively short (<50μs), since the quantity of material involved is small (the liquid crystal is only tens of microns thick) and thus thermal inertia is of negligible importance. On the other hand, there is no prohibition on the use of a relatively long line access time, several tens of milliseconds, for example, or using the internal memory of the smectic liquid crystal screen, since one can always adapt the line access time to the arrival rate of the information. Since good resolution and half-tones are possible by optimization of certain parameters, electronic devices for the projection of video TV images are also foreseeable.

There is also a Guest-Host Smectic Effect wherein the addressing scheme is similar to the thermal effect in that it uses thermal addressing on one set of electrodes and field effect on the other set of electrodes. In this case, a dichroic dye is mixed in with liquid crystal. In the scattering state, the dye molecules strongly absorb the reflected light, while in the aligned state, the absorbtion is only partial. Although the contrast ratio may be somewhat degraded, there is an improvement in the viewing angle. However, there appear to be no displays yet incorporating this effect.

An electrically-induced, dynamic-scattering effect in Smectics was first described by Tani (3.3.29) and the application to displays by Coates et al (3.3.50) and Crossland et al (3.3.19). Crossland described the application of an electric field at higher frequency or at the same frequency but at a voltage less than the threshold voltage for scattering to re-align the liquid crystal in the transparent state.

3.3.2.10 Smectic Displays

In the device described by Kahn, information is written by localized heating with a laser beam. An electric field is applied to transparent electrodes on the glass walls of the cell. The resolution is high with a pixel diameter of 10 to 20 μm but the addressing time is long, typically, 5 seconds per frame for a 1.2 by 1.2 cm device having 1024 lines of 10 μm width. In the display described by Hareng et al (3.3.18), the inner walls of the cell enclosing the liquid layer are covered with orthogonal sets of electrodes, at least one of which is transparent. A unique feature is the use of two different and independent effects; thermal effect on the lines, electric field effect on the columns. When a current is passed through a line electrode, which acts as a heating resistor, the material goes locally into the isotropic phase along that line. The video data is put on the column electrodes while the line is cooling down. Wherever the video is higher than a certain threshold value, the material will be re-aligned and be transparent. Because the video voltage affects only the line which is cooling down, there is no voltage limitation due to the crosstalk effect which would occur in other matrix displays. The display resolution is 240 x 250 pixels over an area of 94 x 90 mm on which 25 rows of 6 x 10 dot matrix symbols could be displayed.

A simple addressing scheme proposed by Crossland and Ayliffe (3.3.19) involves scattering all picture elements by a single pulse applied simultaneously to the whole display (page blanking), followed by scanning down the display, line by line, selectively erasing the scattering by promoting the focal conic to homeotropic transition. For display cells of this type, erasure is calculated to require a single 10 ms pulse of 180 V, which falls to 120 V for a 100 ms pulse. The page blanking voltage (once per frame scan) varies from 300 V for a blanking time of 50 ms to 170 V for a blanking time of 200 ms. Other displays which exploit smectic material are discussed in 3.3.6.2.

3.3.3 OTHER PHYSICAL CHARACTERISTICS

3.3.3.1 Materials

Many requirements are placed on materials in order that they be generally acceptable. First, it is vital that they should be non toxic, both for ease of handling during manufacture and to avoid risks caused by breakage during use. Secondly, they should be highly stable, not only to ensure long life in the operating environment, but also to avoid the need for difficult and costly manufacturing processes. Many of the early liquid crystal materials were suspect on account of either toxicity, susceptibility to atmospheric oxidation or to degradation caused by blue or ultraviolet light. Although some other families now meet these requirements, the discovery of the biphenyl family (3.3.20 & 21) however, first provided a satisfactory solution to these problems. Indeed, some manufacturers now claim operational lifetimes in excess of 30,000 hours.

3.3.3.2 Temperature

Temperature has many effects on LCDs. The most important consideration is the range over which the material remains liquid crystalline. This is bounded, of course, at high temperatures by the transition to an isotropic liquid crystal phase of higher order or at low temperatures to a solid phase. The nematic to isotropic transition is well defined, but solidification is often accompanied by extensive super cooling. It is most important that the quoted minimum temperature for a material represents melting from the solid and does not rely on super cooling: the super cooled state is only metastable, and damage to the surface alignment layers is possible if repeated solidification occurs. Single chemical compounds are rarely liquid crystalline over a usably wide temperature range, but multi-component mixtures have been developed (3.3.22) which have nematic phases over a wide range. Figure 3.3.10 shows the phase diagram of a two component mixture of biphenyls, where the eutectic composition is nematic from 20°C to 70°C. By adding precisely determined quantities of other materials a multi-component eutectic can be made with even wider range. For example, the four component mixture E7 (BDH nomenclature), used in watch displays, typically operate from -10°C to +60°C. More recent mixtures have considerably extended this range and at the same time afforded improvements in other material parameters.

3.3.4 ADDRESSING/DRIVING OF NON-SMECTIC DISPLAYS

3.3.4.1 Matrix Addressing

LCDs generally operate at low voltage with respect to many other displays, typically less than 10 V and as low as 1.5 V. This low voltage/low power and limited display content (e.g., 8-10 digit calculator) have led to single chip/logic driver combinations.

The simplicity of this mechanization has led to low cost, high production. A complex display is arbitrarily defined here as one to which the number of connections is less than the number of individually selectable display elements. As the complexity increases, the mechanization gets to be more difficult. In very complex displays, it is not possible to make separate connections to each element; the display has to be addressed by multiplexing or matrix addressing (see section 2.2.2). There are, however, reasons that liquid crystal displays are difficult to matrix address: For the example given above, a display of numerics using a seven segment format, a row of 10 digits requires 70 elements to be addressed. To supply a driver and connector wire to each of these elements is obviously uneconomical as well as physically cumbersome. For alphanumeric displays, where each character requires at least 35 dots, the problem is obviously far more severe. The solution is to use a matrix addressing method. The transparent conductors on both cell plates are patterned so that each electrode is shared between several display elements. The behavior of this arrangement is electrically equivalent to that of a rectangular matrix of n-lines and m-columns, the cross-points representing the display elements. The minimum number of connections is obtained when n=m, but even with n=3, the number of connections to the above 10-digit example is reduced from over 70 to less than 30.

A simple way of addressing a matrix display is shown in Figure 3.3.11. The lines of the display are scanned repetitively in sequence by a "line select" pulse of amplitude V_R. While each line is selected, the appropriate "select" and "non-select" data pulses, of amplitude $\pm V_D$, are applied to the columns. The liquid crystal elements respond to the root mean square of the difference between the line and column waveforms. Net ac drive is achieved either by reversing the drive polarity after each scan or by replacing each pulse by an alternating waveform.

A problem arises when supposedly "off" elements experience a significant drive voltage, largely composed of the data pulses, to all other elements in the column. The ratio of RMS voltages applied to "on" and "off" elements, and therefore the display contrast may be maximized by correct choice of V_R and V_D. Alt and Pleshko (3.3.23) have shown that, for a display consisting of n lines, maximum voltage ratio is achieved when $V = \sqrt{n}V_D$. This relationship is very important for large values of n, but for values of n around four, a convenient solution is $V_R=2V_D$.

The importance of this optimization is apparent when the liquid crystal characteristics such as acceptable contrast, angle of view and temperature range are considered. Figure 3.3.4 showed the transmission versus voltage at both normal incidence and 45^o from normal in the low voltage quadrant of a TN cell. Figure 3.3.12 shows normal incidence transmission plotted against voltage over a wide temperature range. Satisfactory viewing over a wide angular and temperature range requires:

a) the value of V_{OFF} must be below threshold at the most oblique viewing angle at the highest temperature.

b) the value of V_{ON} must have adequate absorption at the steepest viewing angle at the lowest temperature.

The multiplexed performance of a display at a fixed temperature, therefore, depends on the steepness and angular dependence of the threshold curve of the material used and may be characterized by various figures of merit. For example, the ratio of voltage giving

10% transmission at normal incidence to voltage giving 90% of maximum transmission at 45° incidence immediately shows how many lines may be multiplexed at that temperature. The material E7 mentioned earlier, which was not designed for multiplexing, has a figure of merit of about 1.9. This is scarcely adequate for even 3-way multiplexing with full contrast over this angular range. Alternative materials, however, have been developed with figures of merit as low as 1.6 which give quite presentable performance in 16-way multiplexed reflective displays.

The large values of dV/dT of most liquid crystal materials preclude multiway, multiplexed operation over a wide temperature range with fixed drive voltages. Accurate methods for temperature compensation of drive voltage have been developed which can maintain the visual appearance of displays over practically the entire temperature range that the material is liquid crystalline. These methods either involve a thermistor or other temperature sensor mounted close to the display cell, or may use the liquid crystal material as its own temperature sensor. This latter method (3.3.24) makes use of the dependence of liquid crystal capacitance on temperature and voltage, and has the advantage of sensing temperature at exactly the right place and with no time delays. In spite of the achievable accuracy of temperature compensation, it is still advantageous to use materials with small temperature coefficients in order to minimize the effects of temperature gradients across the cell. To date, one of the most complex alphanumeric displays based on a reflective TN cell, contains 4 rows of 40 characters, complete with cursor line. The drive method uses 16-way multiplexing, and operation from 0°C to 40°C is achieved. The viewing angle ranges from normal to about 40° from normal in the low voltage quadrant, but the precise location of this cone of high contrast can be varied by adjusting the drive voltage.

3.3.4.2 Improvements in Drive Methods

The Alt and Pleshko optimization of drive voltages mentioned in Section 3.3.4.1 assumed a rather restricted type of waveform where only one voltage ratio was adjustable and where the addressing waveforms depended in a very simple way on the data to be displayed. Clark, Shanks, and Patterson (3.3.25) recently considered the potential of completely generalized drive methods. The conclusions of these approaches are that, in general, improvements are possible, but these improvements are only significant either when the number of scanned lines is very small or when the number of elements per column which are different from the background, is very small. Clearly, neither of these conditions pertains to complex alphanumeric displays, but the application of this type of approach to various special purpose displays is discussed in section 3.3.6.1.
Also, see Chapter 2.2.3 & 2.2.4.

3.3.4.3 Exploitation of Alternative Liquid Crystal Effects

Although there are many liquid effects that might eventually be exploited, the two effects mentioned here have been chosen because of existing demonstrations of their capability although still others could be described as well. The first, known as "two-frequency multiplexing", uses the optics of a conventional TN display, but incorporates nematic materials having unusual dielectric constants with applied frequency. There is a critical frequency f_c, known as the "cross-over" frequency, at which the two values are equal. Below f_c, the parallel dielectric constant exceeds the perpendicular, so a low frequency field tends to turn the display on. Above f_c the reverse is true, so a high frequency field tends to turn the display off. A few useful materials exist having an f_c in the range 1-10 kHz at room temperature. This effect has been exploited by van Doorn and de Klerk (3.3.26), and by Hosakawa et al (3.3.27) where for both cases, high and low frequency drive signals were applied simultaneously. The selection of on and off elements was done via the high frequency signals. The low frequency signal, of constant amplitude, effectively counterbalanced a large part of the effect of the high frequency signals. An analysis of this approach is given in 3.3.28, showing how the number of lines that may be multiplexed increases with the available drive voltage. The main problem with method is the variation of f_c with temperature; typically, f_c doubles with every 8°C rise. Consequently, the total temperature range of the method is restricted to perhaps 40°C by the range of practicable drive frequencies. The demonstration of this method by Hosakawa used 56-way multiplexing to generate 8 rows of 64 characters. Drive amplitudes were restricted to 40V peak-to-peak, and the temperature range covered was 0°C to 40°C. The second method, developed by Tani et al (3.3.29) exploited hysteresis and storage effects sometimes found in the characteristics of the cholesteric-nematic phase change effect. Both clear and scattering states were obtained that remained stable for several hours at room temperature, and a method was achieved of switching between these states in a few milliseconds. The largest display consisted of 306 lines of 574 dots at 0.4mm pitch and was driven with +14V. The contrast ratio was 24:1 and the angle of view was greater than +70°. However, no information was given on the temperature range of these displays. These are among the most complex multiplexed LCDs yet demonstrated, and are probably capable of further development, especially possible with the incorporation of the pleochroic dyes mentioned in section 3.3.2.6.

3.3.4.4 Incorporation of Integral Electronic Components

The advantage of this approach is that it makes only minimal demands on the steepness of the transmission-voltage characteristic of the liquid crystal. The complexity resides in the cell substrate, where an electronic device, either active or non-linear passive, is placed in series with each liquid crystal element. The electrical characteristic of each device must achieve two objectives; first, it must block all partial select pulses addressed to other elements; second, when a full select pulse occurs it must permit the capacitance of the liquid crystal to charge up rapidly, and when this pulse ends, prevent the charge leaking away until the next select pulse occurs. Three approaches have been pursued: active silicon substrates, thin-film transistors on glass, and varistors.

3.3.4.5 Active Silicon Substrate Address

The Si Substrate approach of Lipton et al (3.3.30), Figure 3.3.14, used a complete 3 inch (7.62cm) diameter Si slice as one side of a 1.75 inch (4.45cm) square dynamic scattering display. On this substrate was a 175 x 175 array of fairly conventional MOS FETs, addressed via an x-y matrix of conductors. A silver reflector was provided for each display dot. The display drive circuits operated at a TV compatible rate of 30 frames per second, and had a grey scale capability of 5 as well as a contrast ratio of more than 20:1. This approach has considerable potential for further development with the inclusion of decode and drive circuits on the same slice (3.3.31) and the use of the DPC effect for better appearance (3.3.32), higher resolution, etc. A brief discussion of this device and how it was mechanized in a display follows:

The first display substrate developed, a 100 x 100 element, one inch (2.54cm) square, liquid crystal matrix display, was demonstrated in September 1973. The one inch (2.54cm) square format was the largest size that could be constructed, at that time, using a two inch (5.08cm) diameter silicon wafer. The first defect free device of this type was completed in June of 1975. In recognition of the need for a larger display with high resolution, a two inch (5.08cm) square "quad" display, constructed of four one inch (2.54cm) chips, was demonstrated in December of the same year.

In 1976, a transition was made to a 3 inch (7.62cm) diameter silicon wafer processing and the design of a 1.75 inch (4.45cm) square 175 x 175 element display was begun. The first of these devices was completed in 1977. The liquid crystal medium selected for use in this application was a dynamic scattering material compounded for long life under dc operation. This effect was chosen because it was compatible with MOS drive circuitry and had sufficient speed and grey shade capability to provide real-time video images. Other materials, such as Guest-Host (DPC) materials with newly developed stable pleochroic dyes could have been used.

Figure 3.3.15 illustrates the construction of such a matrix liquid crystal display. The liquid crystal material is sandwiched between a cover glass, coated with a transparent electrode (indium tin oxide), and a semiconductor chip. This chip also contains one storage capacitor and one switching field effect transistor for each display element, and line and column bus electrodes. The column busses connect to the drains of the transistors at each element in their respective columns. Similarly, one line electrode connects to the gate of each transistor in the corresponding line. Line-at-a-time addressing is used to form an image on the display. To write one line, voltages proportional to the amplitudes of each element are placed on the column electrodes. A voltage is applied to the appropriate line electrode, the transistors in the line conduct and each element storage capacitor charges to the voltage applied to the corresponding column electrode. The storage capacitors hold sufficient charge to energize the liquid crystal layer until the line is rewritten during normal 30 to 60 Hertz refresh. The display is generally viewed with a light trap as shown in Figure 3.3.16. The scattering elements appear bright on a dark background. While this arrangement provides displays with high contrast, the external light trap restricts viewing angle, adds an undesirable structure in front of the display, and complicates illumination of the liquid crystal surface. Combining the four substrates into a single large direct view display did not meet with success. The overall viewing angle was restricted both with respect to the observer and the incident light necessary for illumination, but provide an adequate display. However, the process of sawing the edges to be butted, damaged the leads and the seals. The conclusion is that at this time, the overall area is restricted to that obtainable to a single Si slice until some reliable method of sawing and butting substrates together is developed. Recently, several companies have demonstrated prototype TV displays using this silicon substrate approach (3.3.31 & 3.3.32). Typical display sizes are 2.5 cm diagonal, with over 200 horizontal and vertical lines. Various of the nematic and cholesteric optical effects have been used to overcome the viewing restriction mentioned above.

3.3.4.6 Thin-film Transistor (TFT) Address

The thin-film transistor approach is electrically very similar to the silicon addressed approach in that each display element is addressed via a FET, but it has the advantage that the substrate is a glass sheet on which all components are vacuum deposited, thus the size limitation of the Si slice is eliminated. The work of Brody et al (3.3.33) was based on a 6 inch (15.24 cm) square display with 180 x180 elements. The semiconductor was CdSe, produced in polycrystalline form by vacuum evaporation followed by careful annealing. While in this case the TN effect was used, in principle any other liquid crystal effect could be used. Both alphanumeric and video display modes were demonstrated, the video being refreshed at 60 Hz and achieving 6 shades of grey. The characteristics of TFTs made of amorphous Si on glass are also well suited to this application (3.3.34). This material can be readily deposited over large areas in thin-film form by various methods. Ultimately, it may prove to be an easier material to control, requiring simpler processing and producing FETs with more suitable characteristics and provide the possibility to incorporate all the drive electronics.

3.3.4.7 Varistor Addressing

The third approach, developed by Castleberry (3.3.35) uses a slice of the varistor material, ceramic zinc oxide, as the display substrate. Careful design of the conductor configuration on this substrate ensures that each liquid crystal element is directly in series with a varistor. The extremely sharp knee in the I-V characteristic of this material is used to discriminate between partial select and full select pulses. A cell (5 cm x 12.7 cm) divided into a 70 x 175 dot matrix, was used to simulate the behavior of up to a 250 line matrix. The DPC effect is used producing very good contrast and viewing angle with a black dye mixture. Substrates up to 8 inches (20.3 cm) diameter have been demonstrated. The Varistor Addressed LCD shows the promise for use as an alphanumeric medium resolution graphics display. Currently being developed for use in a programmable control unit, the display will have a pixel density of 36 per inch (14.2 pixels per cm) in a 180 x 250 line format. The resolution density is currently limited by the varistor geometry, but is expected to reach 80 pixels per inch (31.5 pixels per cm). The display currently employs some organic materials, thus is not yet employable in the military environment. However, current research with inorganic materials promises a near-time solution.

At this time it is difficult to predict which of these approaches (i.e., Si-Substrate, Thin-Film Transistor, or Varistor) has the most potential. Each has the potential of addressing several hundred lines of data, but each also requires considerable technological skill and advancement, so the ultimate choice will most probably depend on size, resolution, and achievable yields.

3.3.5 VISUAL CHARACTERISTICS

In the previous discussions, the principle visual aspects have already been addressed. Generally speaking, direct view TN and similar LCDs do not appear bright, mostly due to the need for a polarizer. As noted earlier (e.g. 3.3.2.7 & 3.3.2.8), new techniques may obviate this problem. In any event, luminance-contrast levels are considerably better in projection systems. The cost to achieve these results is increased depth, volume, and power. For simple graphics and alphanumerics, the 1.75 inch (4.45 cm) high resolution display is readable in an ambient of 100,000 lux, but requires supplemental illumination at moderate and low light levels.
The contrast of most TN types are angle dependent, especially as the number of lines multiplexed goes up. Angle dependence will also be present in any display which is affected by birefringence. Fortunately, a convenient method to measure contrast was proposed by Penz (3.3.36). Again, as an example, the 1.75 inch (4.45 cm) display has a solid 20° (cone) angle wherein contrast ratios of up to 20:1 have been measured.

The birefringence effect is also a factor of material thickness and temperature, resulting in unwanted "color" changes. If a twisted nematic display is fabricated with its optical thickness too small with respect to the wavelengths of visible light, color is observed in the off state of the display. The reason is that the birefringence of the nematic material is no longer strong enough to twist the incident linearly polarized light by 90 . Elliptically polarized light results with the interference colors in white light. Where the thickness cannot be totally controlled, the result is distracting colored bands. Similarly, when dynamic scattering material is used in conjunction with a linear polarizer, the colored bands are not only affected by cell thickness, but temperature, as well (3.3.37).

Color has never been a strong factor in LCDs due to the fact that the displays are not bright, and have not had a great deal of information displayed. Under these conditions, luminance-contrast is much more important than color, per se. Attempts to provide two and three color matrix addressed displays have not been notably successful. One such attempt employing the 1.75 inch (4.45cm) display, used color filters to divide the area into two color bands. The introduction of the filters reduced the luminance-contrast to below useable levels. Another approach is mentioned in section 3.3.6.3. This alternative is a projection system where high luminance is achieveable. Of course, any single color may be obtained by the choice of illumination.

3.3.6 STATE OF DEVELOPMENT

3.3.6.1 Addressing of Displays with Restricted Information Content

As noted in Section 3.3.4.2, improved drive methods could be devised for large matrices, provided that enough restrictions were placed on the information to be displayed. Two examples of this approach are bargraphs and oscilloscopes. A digital bargraph display consisting of a single column of dots would normally display data by having all dots below the indicated level, on, and all dots above that level, off. A liquid crystal display of this type has been described by Kmetz (3.3.38) in which the connections between elements were configured to be electrically equivalent to a conventional matrix. This matrix required few external connections and very few distinct drive waveforms. Nevertheless, the 3:1 voltage ratio between on and off elements ensured high contrast viewing over a wide angular and temperature range. Further extension to the multiplexed drive of double and triple bargraphs was demonstrated with only slightly degraded visual appearance. The oscilloscope scheme of Shanks et al (3.3.39) utilizes the fact that when displaying a single-valued function on a matrix display, only one element per column is different from the rest. In practice, it is convenient to turn the background elements on and hold the data elements off. The method uses a set of different waveforms, one per line, driving the matrix continuously. To obtain an off element at any required line and column intersection, it is merely necessary to apply to the column the same waveform as is applied to the row. The pseudorandom binary waveforms chosen have the advantage that a high, uniform voltage is applied to all on elements giving good contrast and permitting very wide temperature range operation. The entire oscilloscope with a 100 x 100 dot display requires only 60 integrated circuits and consumes less than 500mW. It was demonstrated in reflection with both TN and DPC displays while one model used a transmissive TN display for large projection. Further developments of this approach may be applied to other special purposes, e.g., analog meters and clocks, etc.

3.3.6.2 Light Valve Projection Displays

Of several systems extant, the examples chosen here are representative.

The first, described by Hong et al (3.3.40) was the result of many years of development. The system contained a CRT which acted as a primary image generator and which was optically coupled to a liquid crystal cell either by fiberoptics or by a lens system. The complex liquid crystal cell included a photoconductive layer on which the data was imaged and which controlled the spatial distribution of voltage across the liquid crystal. An earlier laboratory demonstration (3.3.41) using a birefringence effect, gave a multi-color information display with a simultaneous black-grey-white capability. However, the stability of the liquid crystals used for this versitile effect was not adequate for commercial exploitation. Polarized projection light was incident on the opposite face of the cell, and was isolated from the photoconductor by a dielectric reflector and a light blocking layer. Different wavelengths in the projection light were reflected, according to the state of the liquid crystal. The projected image then consisted of data in one color on a background of another color, the colors being partially selectable by the operator. The system, which was portable, was capable of producing high contrast images with up to 700 line resolution, but no grey scale.

The second approach was developed by Melchior et al (3.3.42), Dewey et al (3.3.43), and others. As noted in 3.3.2.9, smectic material can exist indefinitely in either a transparent, homeotropic aligned state, or a scattering state. The state may be controlled locally, with resolution of a few tens of microns, by laser or resistance heating, either with or without an electric field. In this way, data may be written into the liquid crystal cell, stored, and if necessary, erased or updated. The cell can act simultaneously as the transparency in a simple Schlieren projection system, permitting real-time storage and display of dynamic data. Several variants of the scheme have been made, some used in transmission, others in reflection, with various writing lasers. One of the most complex was capable of completely rewriting the 1500 x 1500 resolution elements in 3 seconds.

A high resolution, four color system in a four foot square format (1.22 meters x 1.22 meters) was recently demonstrated by Tsai and Aitken (3.3.44). The system employs two smectic LC light valves which are thermally addressed by a single laser, respectively. Each light valve is 2.54 cm square and can address 2048 x 2048 pixels.

3.3.6.3 Other Projection Systems

The 1.75 inch (4.45 cm) square silicon substrate display (section 3.3.4.5) had been developed for two other applications. The first, a direct view Horizontal Situation Indicator (HSI) (3.3.37) the second, to be used in a reflective mode in a Head Up display. The HSI employed an integral wedge (Figure 3.3.17) for white (day) and red (night) lighting for low ambients. Although earlier experiments had met with reasonable success, it nevertheless proved impracticable to join the four 1.75 inch (4.45 cm) square substrates. Thus, the quad satisfied neither application. However, the individual substrates can be made successfully and are currently being incorporated into the following configurations.

a) a Head Up display wherein four individual substrates are illuminated and the images optically combined to form a larger virtual image (i.e., the optical equivalent to the quad).

b) similarly, a set of high resolution substrates, each 0.7 x 1.026 inches (1.78 x 216 cm) with a resolution density of 346 pixels per inch (136 pixels per cm) i.e., 240 lines by 320 lines, used in a reflective mode, each illuminated by a single color, and optically combined to yield a multi-color display with the same resolution, the final image being approximately 3.5 x 4.75 inches (8.9 x 12 cm).

c) a third mechanism using a magnifying fiber-optics wedge(s) uses four of the square substrates and combines the images into a single 5.0 x5.0 inch (12.7 x 12.7 cm) display (Figure 3.3.18).

3.3.6.4 Displays with Restricted Angle of View

When reduced angle of view is acceptable, or when projection is used, far more complex displays are possible. One of the most complex was reported by Kaneko et al (3.3.45) where a 120 line TV picture with 160 dots per line and 16 grey levels was demonstrated. The TN effect was used, and the entire TV receiver and display consumed about 5W from a 15V supply. One must assume, however, that since 60-way multiplexing was used, the angle

of view and temperature range of the display must both have been extremely narrow. A more recent version (3.3.46) has achieved better performance with the same 120 x 160 format by using 30-way multiplexing of a more complex electrode structure.
Another TV-type demonstration was by Robert (3.3.47) who used the variable birefringence effect in a negative nematic material as mentioned in section 3.3.2.2. To satisfy the severe tolerance on cell spacing that this effect incurs, the active cell area was restricted to 6.4mm square. A 10cm square image was then produced by projection. The display consisted of a 128 x 128 matrix with 8 grey levels. The response speed at room temperature permitted only 5 images per second, but this rate doubled at 40°C.

3.3.6.5 Improvements in Materials

There is considerable pressure for improved materials for multiplexed displays, and it is clear that gradual improvements are continually being made. However, a major breakthrough would be required to improve the threshold sharpness from its present typical value, capable of 7-way to 10-way multiplexing, to a value that would permit 50-way multiplexing of a reflective TN display. Such breakthroughs seem rather unlikely, so one may only anticipate rather steady progres from this approach. Advances in smectic materials and devices offer alternative means to move beyond these limits. In addition, new materials are also being developed which can be expected to extend the temperature band to about 100°C.

The smectic devices described earlier (Sections 3.3.2.9 and 3.3.3.10) all use a smectic A type liquid crystal material with positive dielectric anisotropy. The rod-like molecules are set nearly at right angles to the plane of the layer. However, different ordering can exist within the layer giving rise to a large number of subclasses of smectics. A novel device uses a chiral smectic material which is ferroelectric (3.3.51). The rod-like molecules are set at an angle to the plane of the layer and appears to increase the speed of the display. Because of stronger coupling with the electric field, Clark and Lagerwall note a much faster response, bistability, and sharp threshold behavior. The bistability arises because the material responds to the polarity of the electric field as apposed to other liquid crystals which respond to the R.M.S. voltage.

3.3.7 SUMMARY

Numeric and alphanumeric liquid crystal displays have found use in a broad range of applications in the consumer market, such as watches, calculators, toys, home entertainment, and even microwave ovens; in the industrial market, such as digital and analog meters, test equipment, and gasoline pumps; in the commercial market, such as alphanumeric and simple graphics for computer terminals, hand-held stock market I/O devices, and automobile instrument panels. As the technology improves and more complex displays develop and enter the production stage, devices will begin to be used by the military. Although a high resolution, television type, display may still be a long way off, prospects are very good for development in the near future of displays having high information content, wider temperature range, higher speed at low temperatures, better visual appearance and improved environmental tolerance. Back-up instruments which employ the Dyed Phase Change effect are to be used in new commercial aircraft (Boeing 757 and 767). For military applications, the initial devices will most likely appear in the form of alphanumeric and low resolution graphic displays since applications such as integrated flight control display systems will require complex displays with complex drive schemes, special filters, anti-reflection coatings and temperature compensation. The lack of sharp thresholds and intrinsic memory of nematic and cholesteric type materials may limit their use to the less complex displays. As noted above, to overcome this, integral electronic components such as thin-film transistors may be required. The use of smectics may fill the gap in some applications, particularly where increased complexity or low yield may delay or rule out present nematics.

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3.3.51	Clark, N.A. Lagerwall, S.T.	A Microsecond-Speed, Bistable, Threshold-Sensitive Liquid Crystal Device, Proc. Conf. Liquid Crystals, Springer Series, Chem. Phys. 11, (1980).

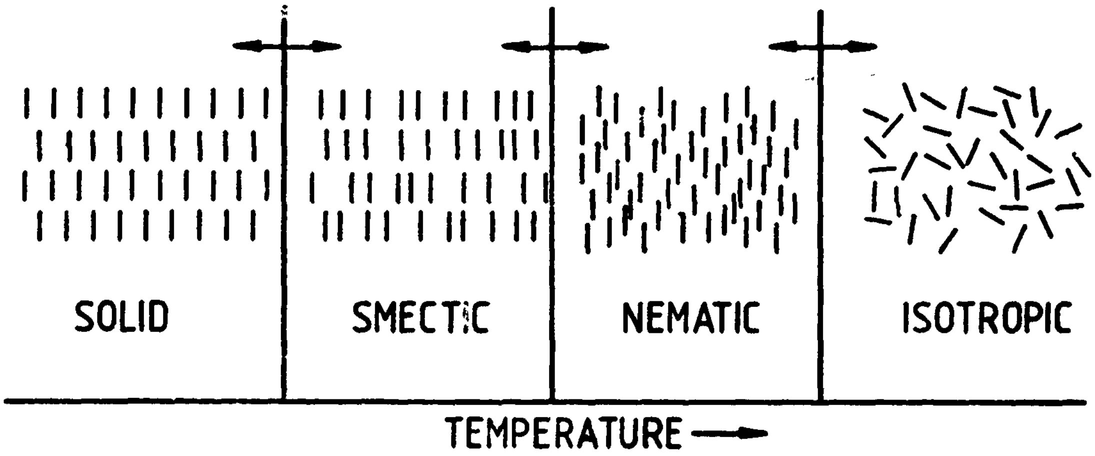

Fig.3.3.1 Simplified phase diagram and schematic structures of hypothetical liquid crystal

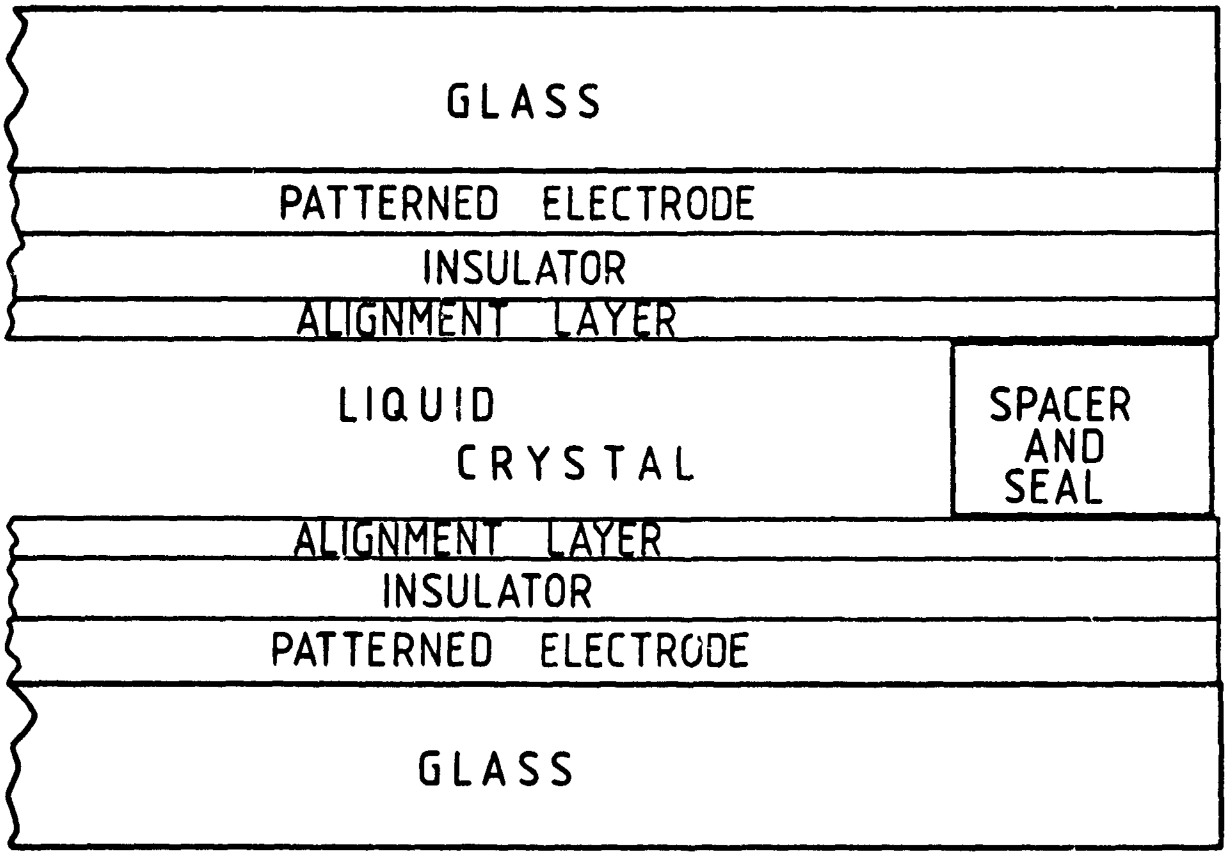

Fig.3.3.2 Schematic representation of a typical liquid crystal cell

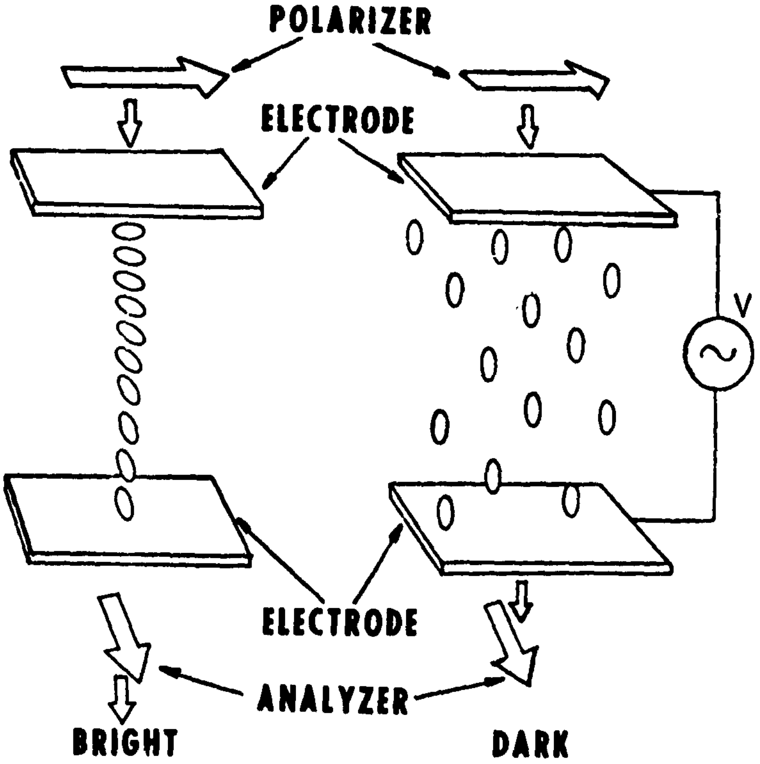

Fig.3.3.3 Twisted nematic cells in ON and OFF states

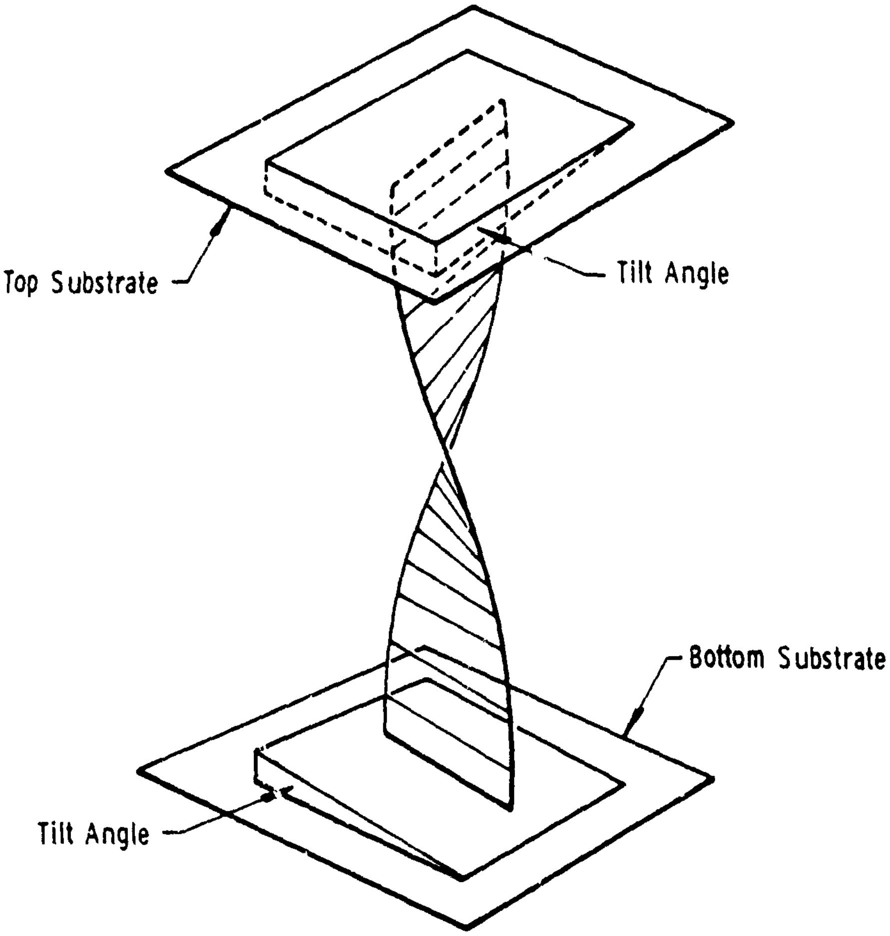

Fig.3.3.4 Twisted nematic structure indicating optic axis response to right angle boundary conditions

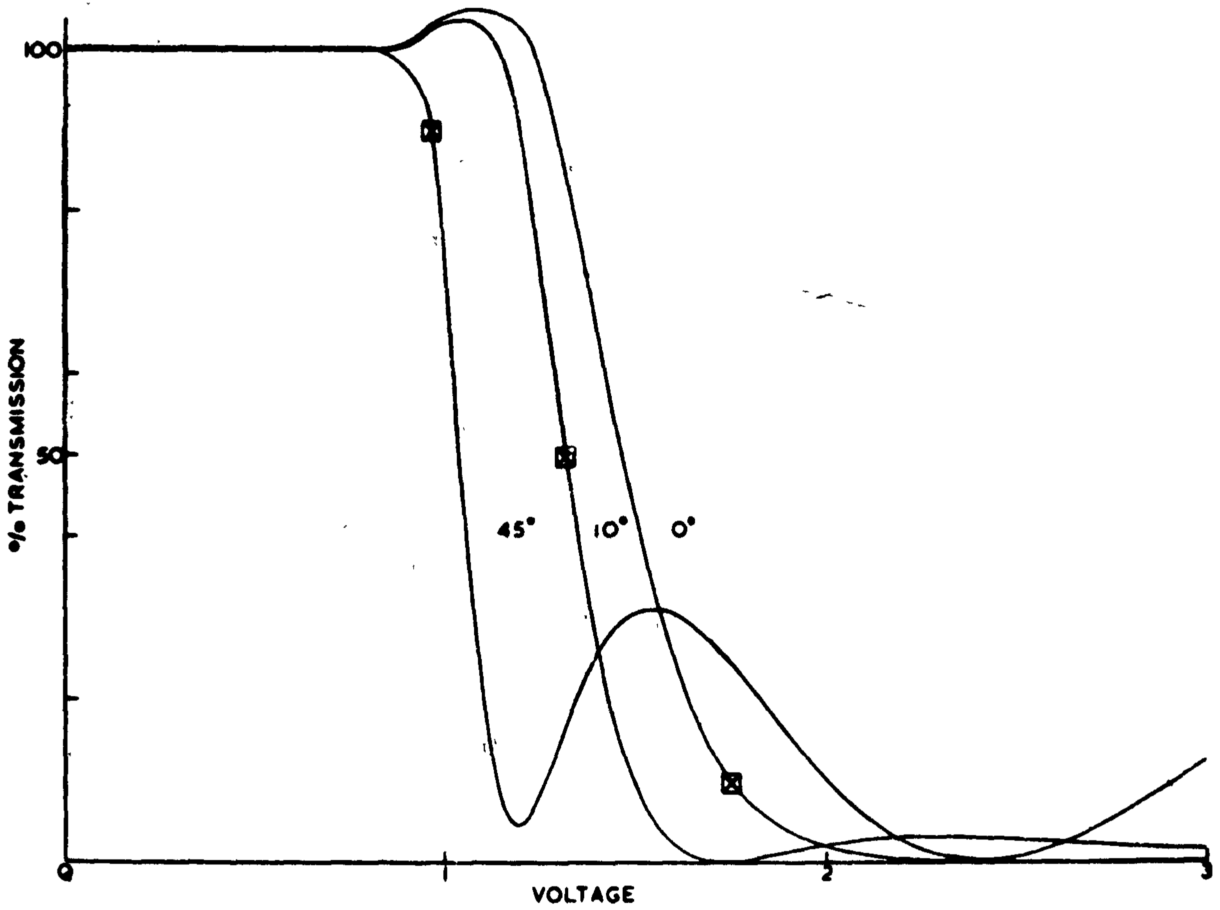

Fig.3.3.5 Normalized optical transmission of a TN cell as a function of applied voltage at three angles of incidence

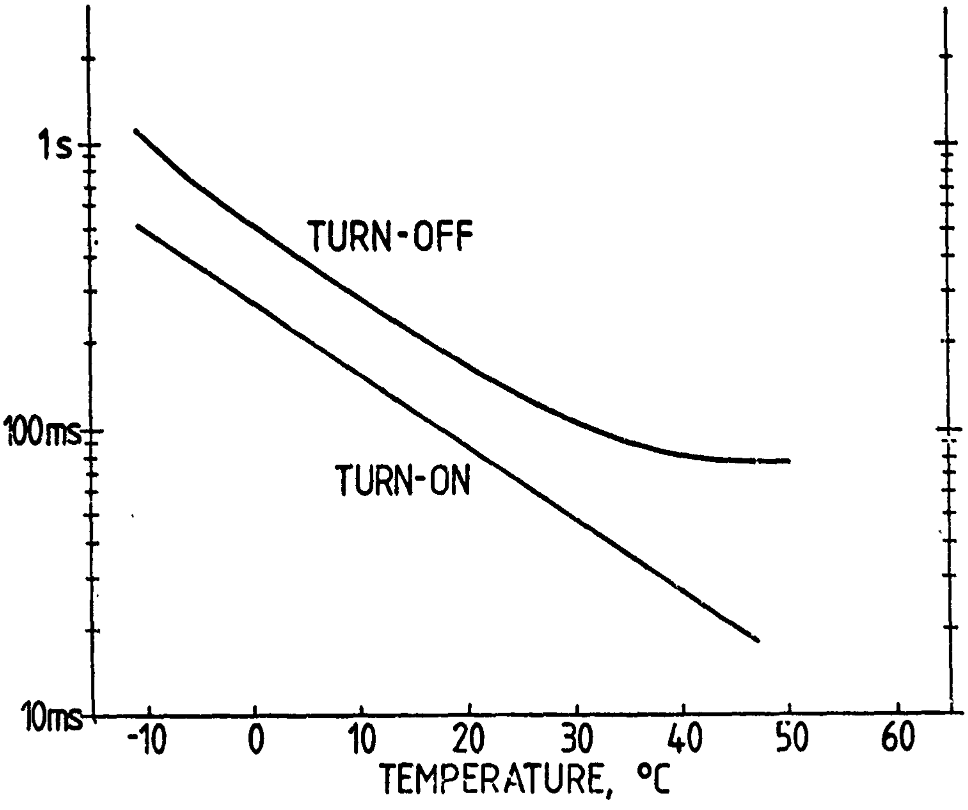

Fig.3.3.6 Variation of response times of a typical TN cell with temperature. Response time is proportional to viscosity and cell spacing

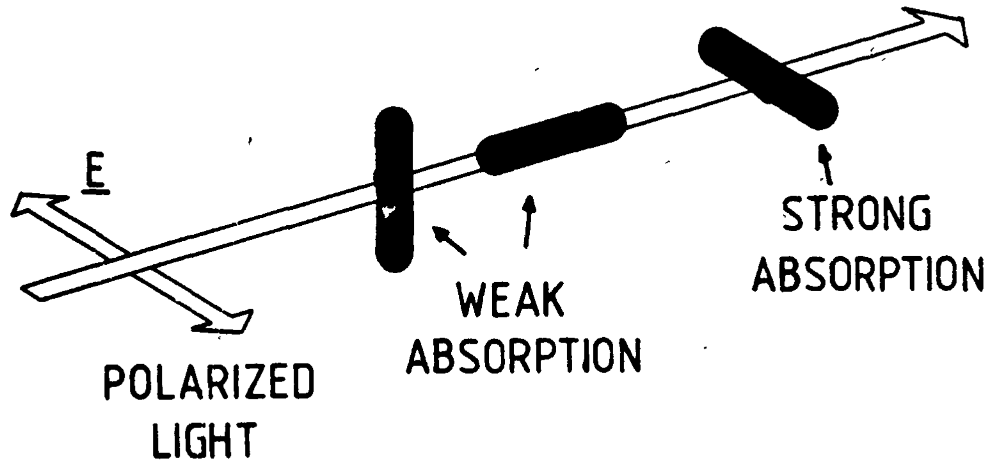

Fig.3.3.7 Anisotropic optical absorption of pleochroic dyes as used in the dye phase-change effect

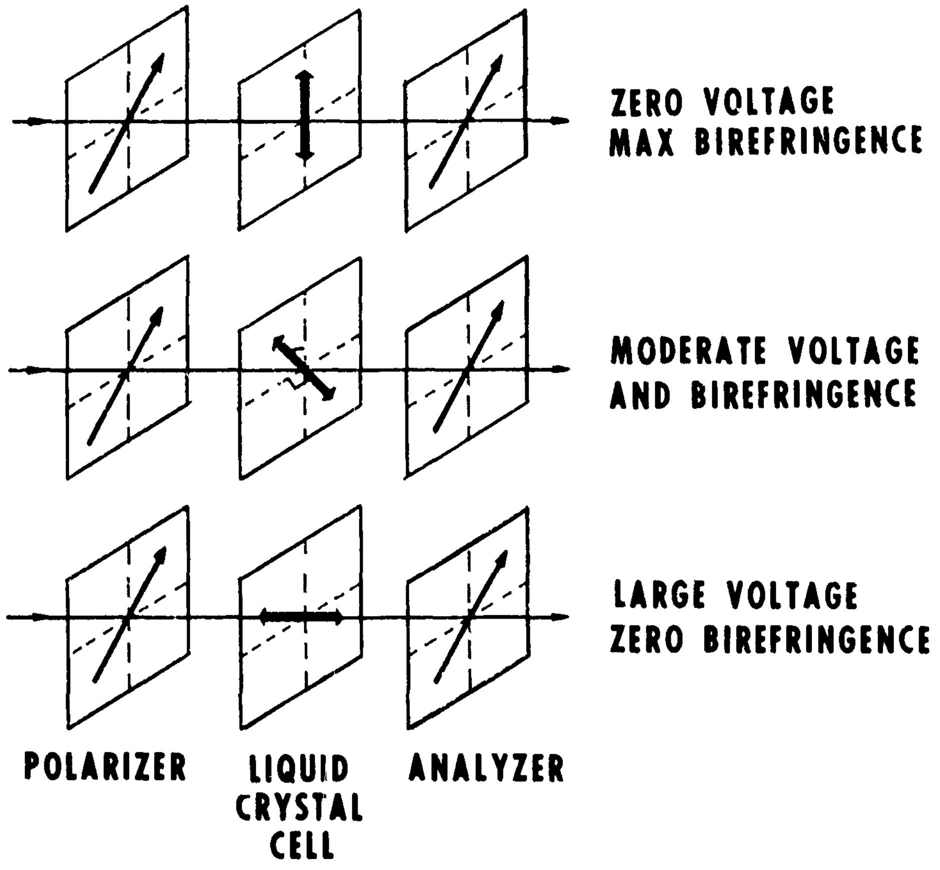

Fig.3.3.8 Typical "variable-birefringence" device at various voltages

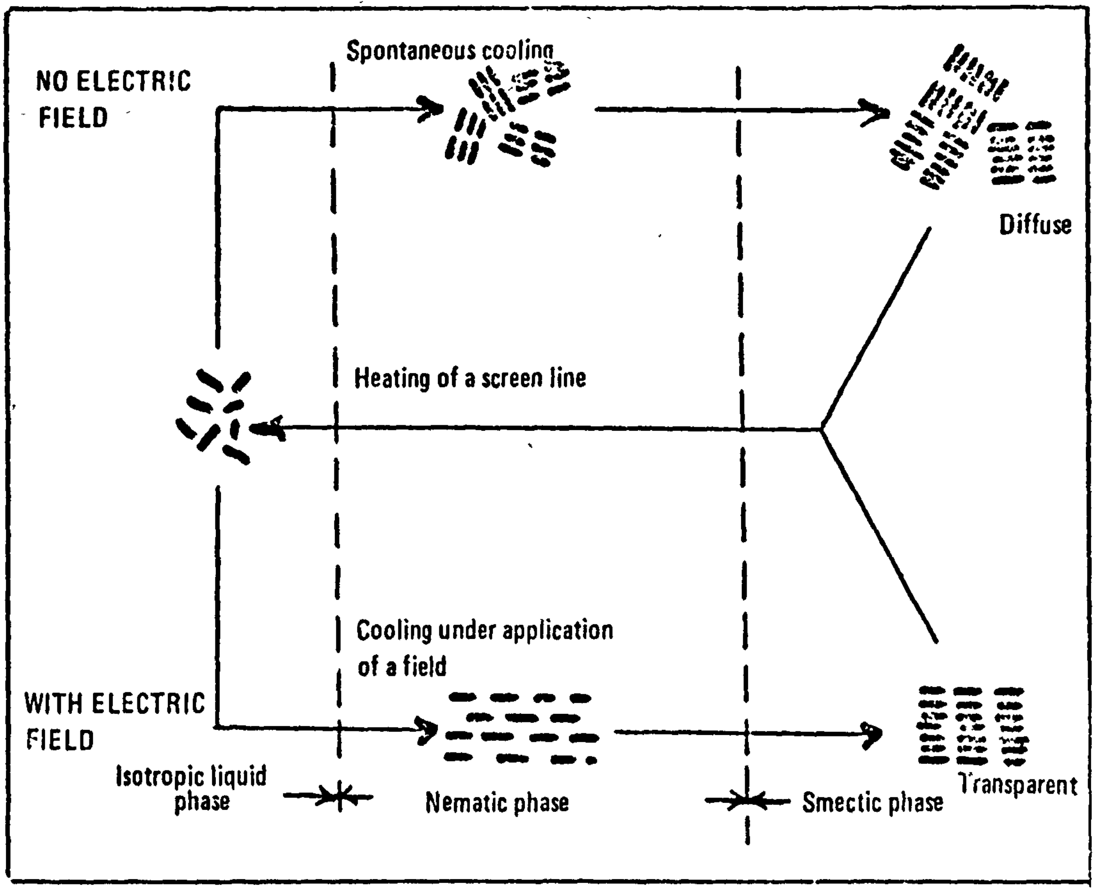

Fig.3.3.9 Thermal and electrical effects with smectic liquid crystals

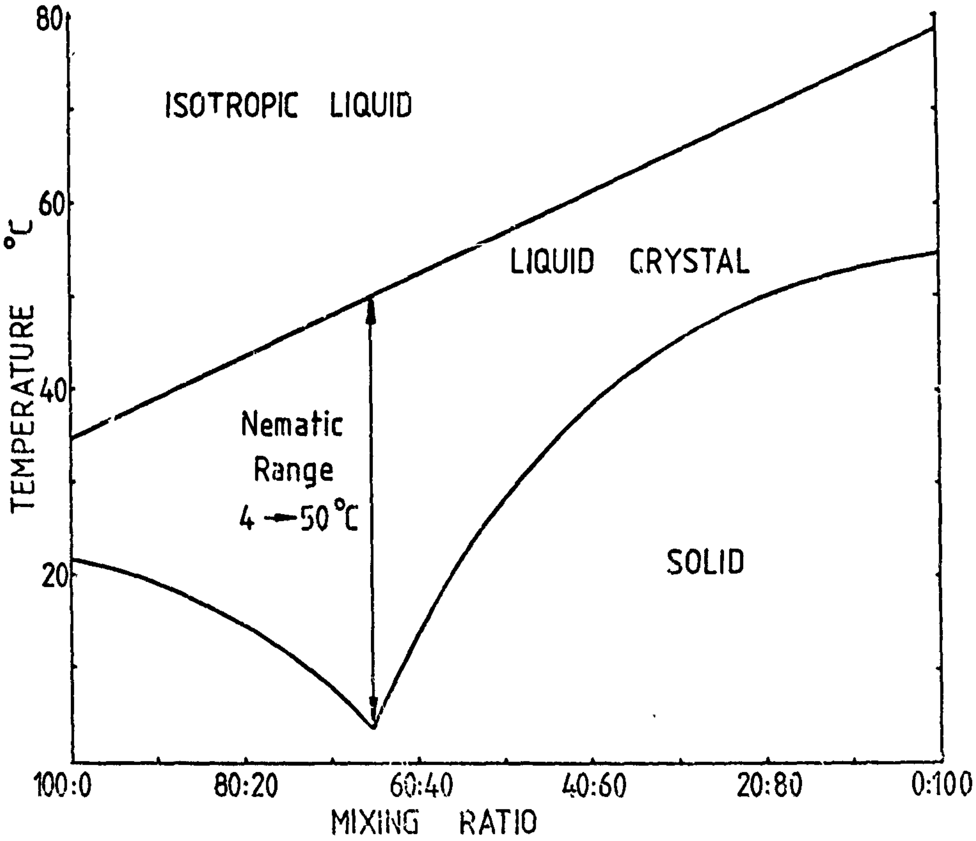

Fig.3.3.10 Phase diagram of a two-component liquid crystal mixture showing wide temperature range of the nematic phase at the eutectic composition

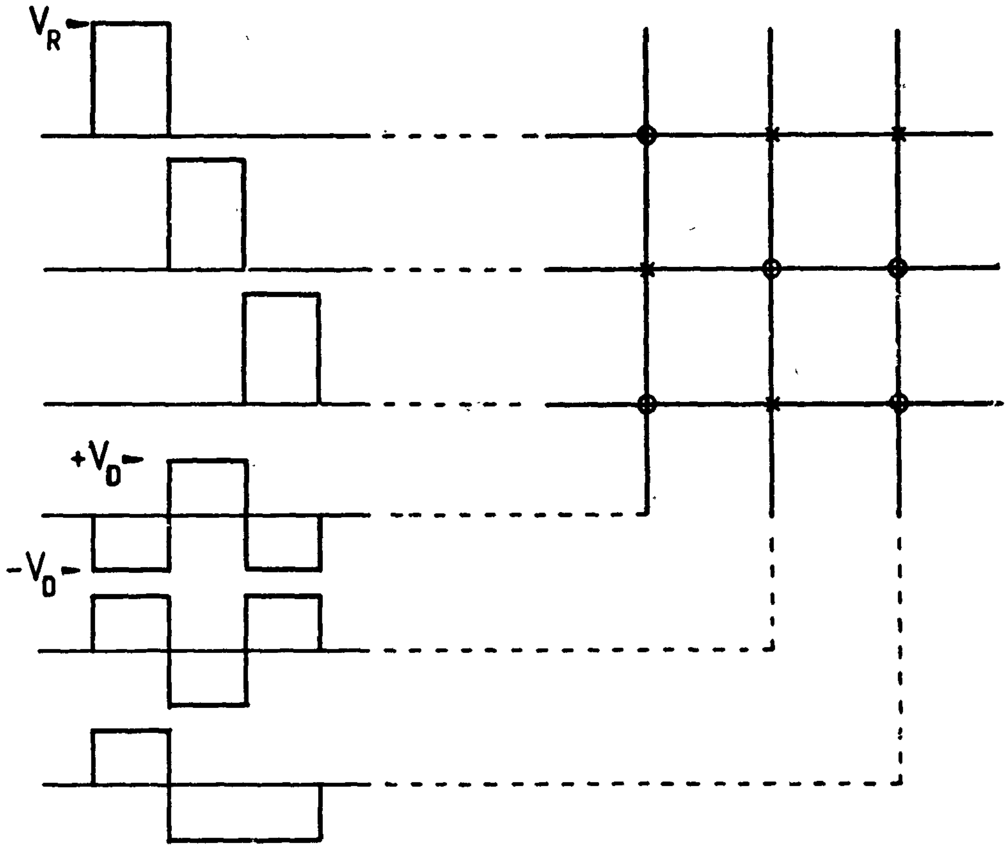

Fig.3.3.11 Simplified multiplex drive scheme

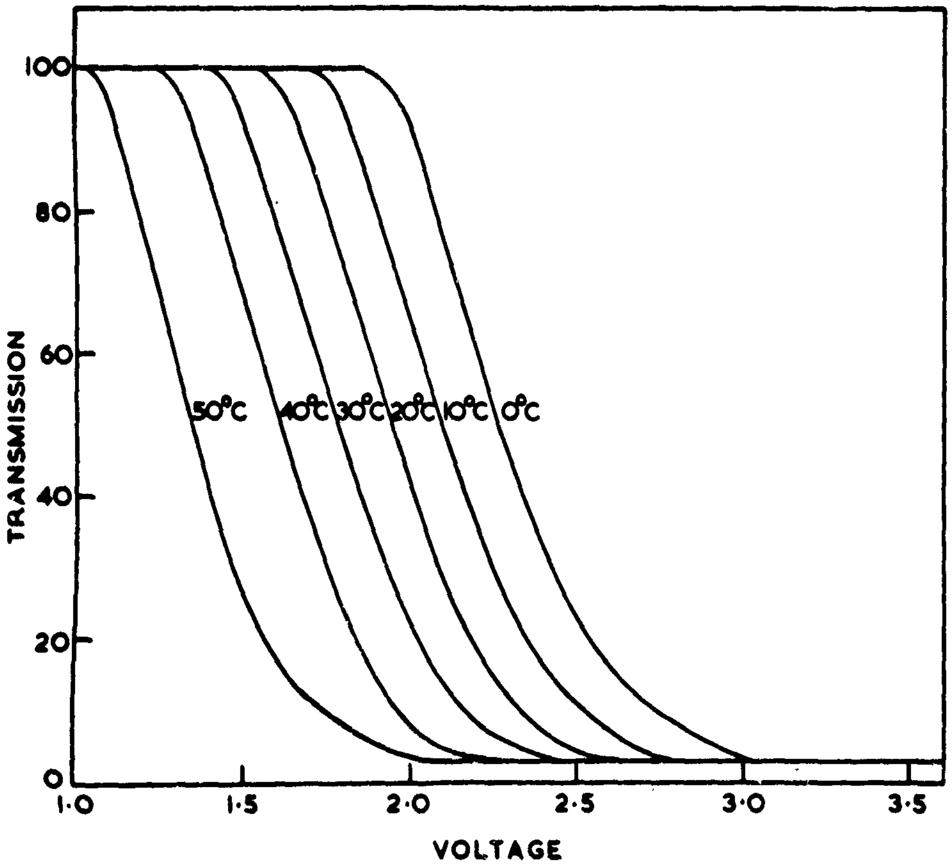

Fig.3.3.12 Variation of transmission vs voltage curves with temperature of a TN cell. Note reduction of threshold with increasing temperature

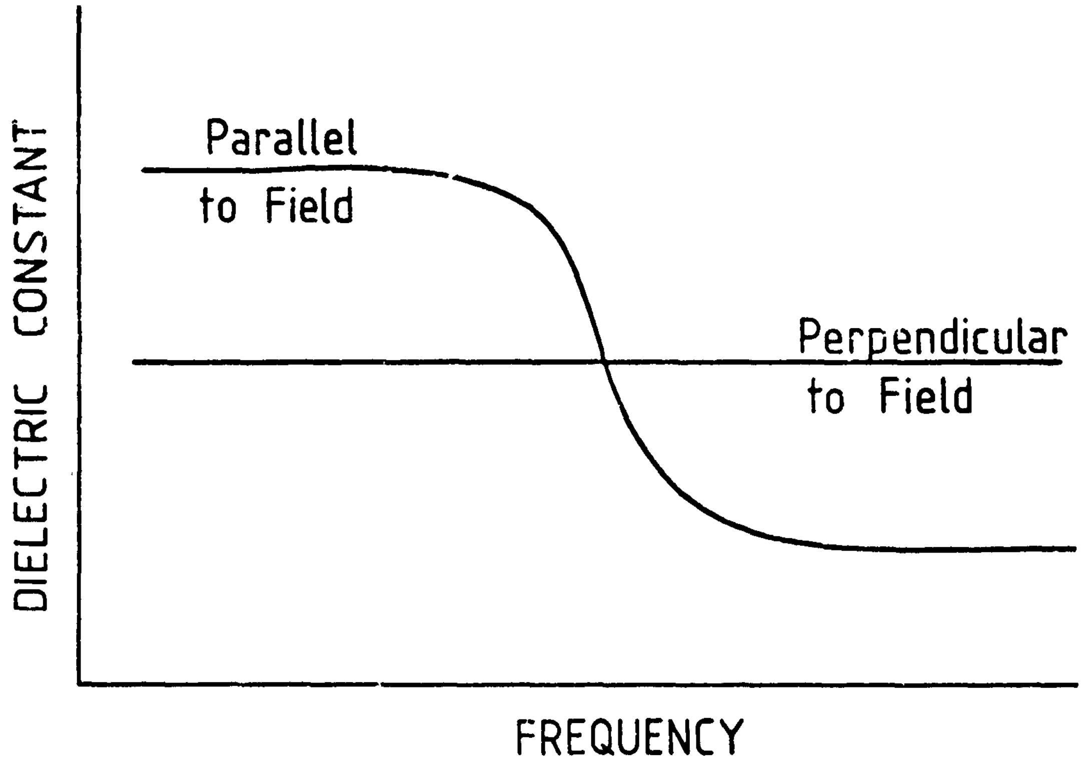

Fig.3.3.13 Two-frequency nematic material; variation of the principal dielectric constant with the frequency of applied field

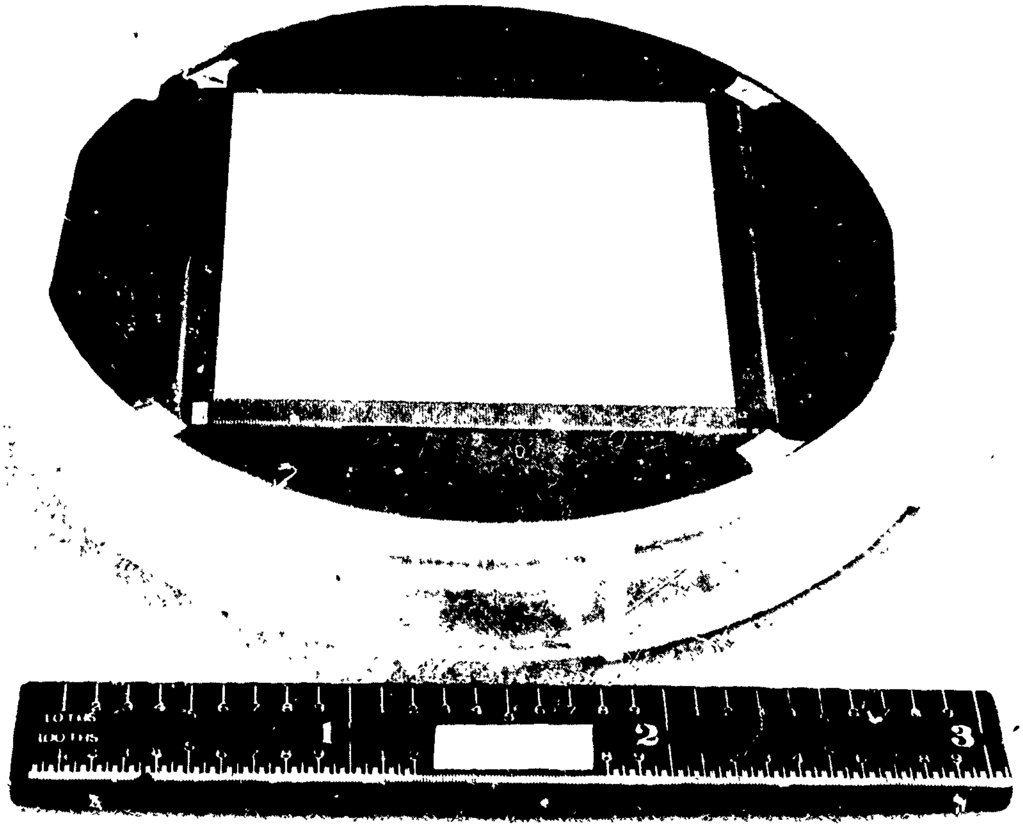

Fig.3.3.14 Silicon substrate-dynamic scattering liquid crystal display

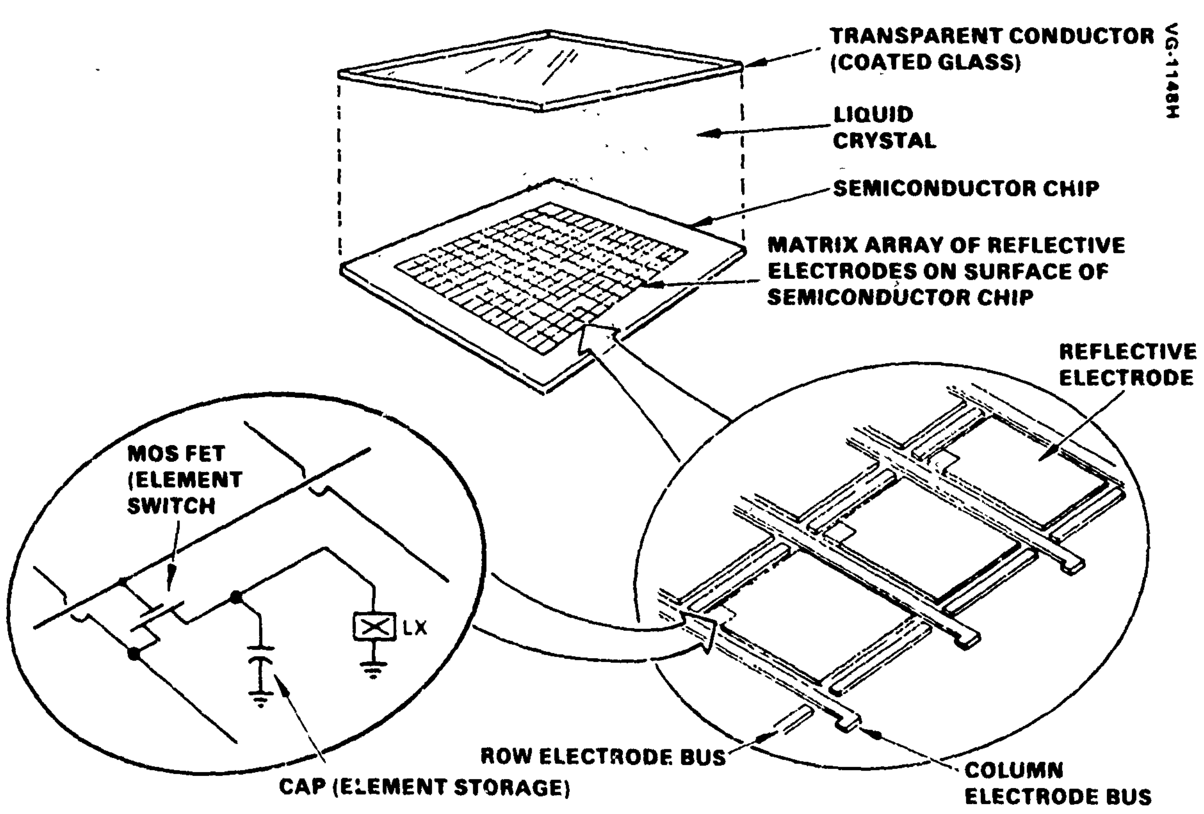

Fig.3.3.15 Silicon chip matrix liquid crystal display construction

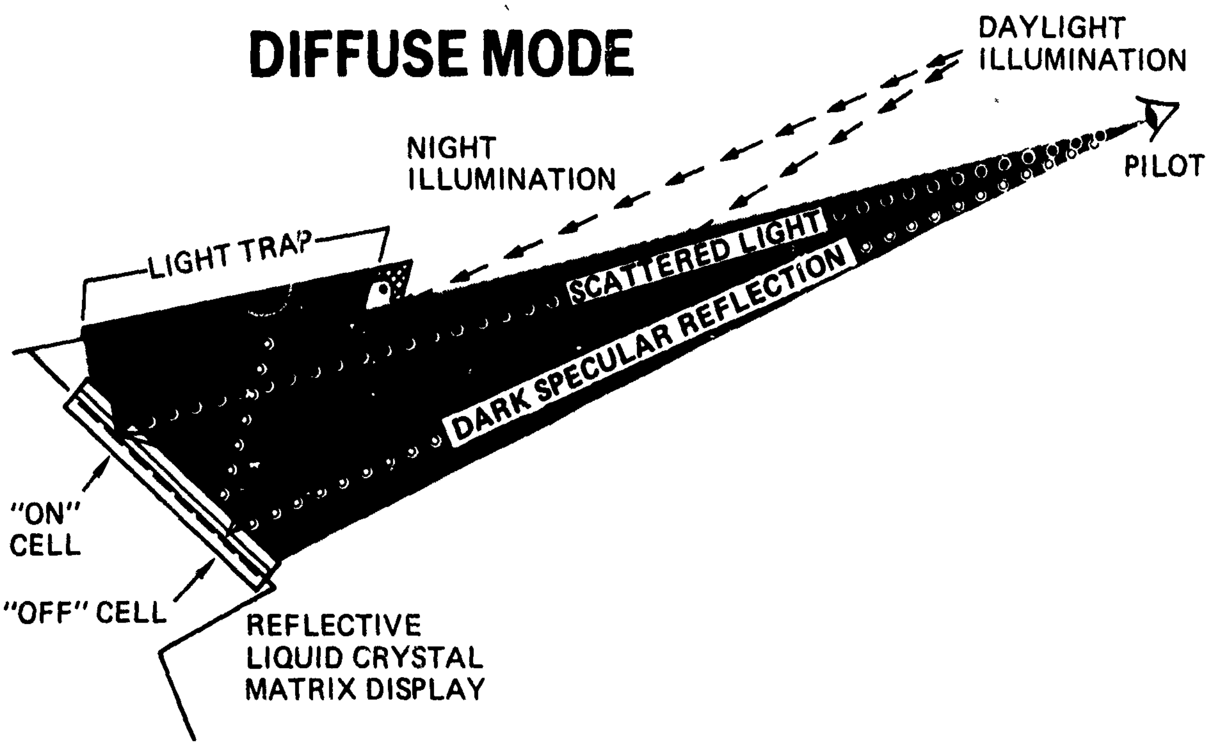

Fig.3.3.16 Direct view dynamic scattering liquid crystal display employing light trap

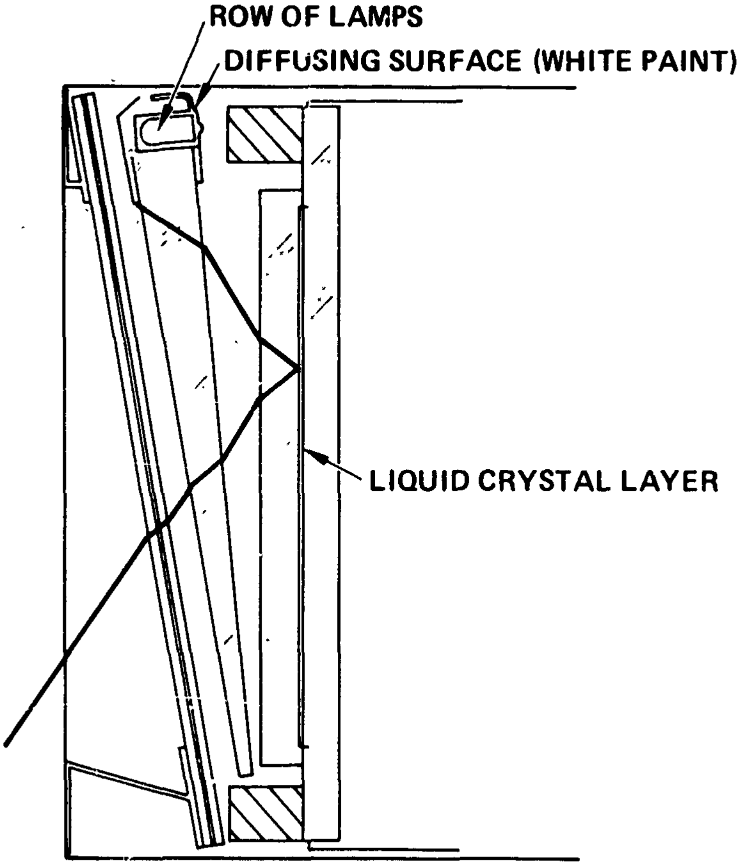

Fig.3.3.17 Direct view dynamic scattering liquid crystal employing an illuminated wedge for day and night viewing

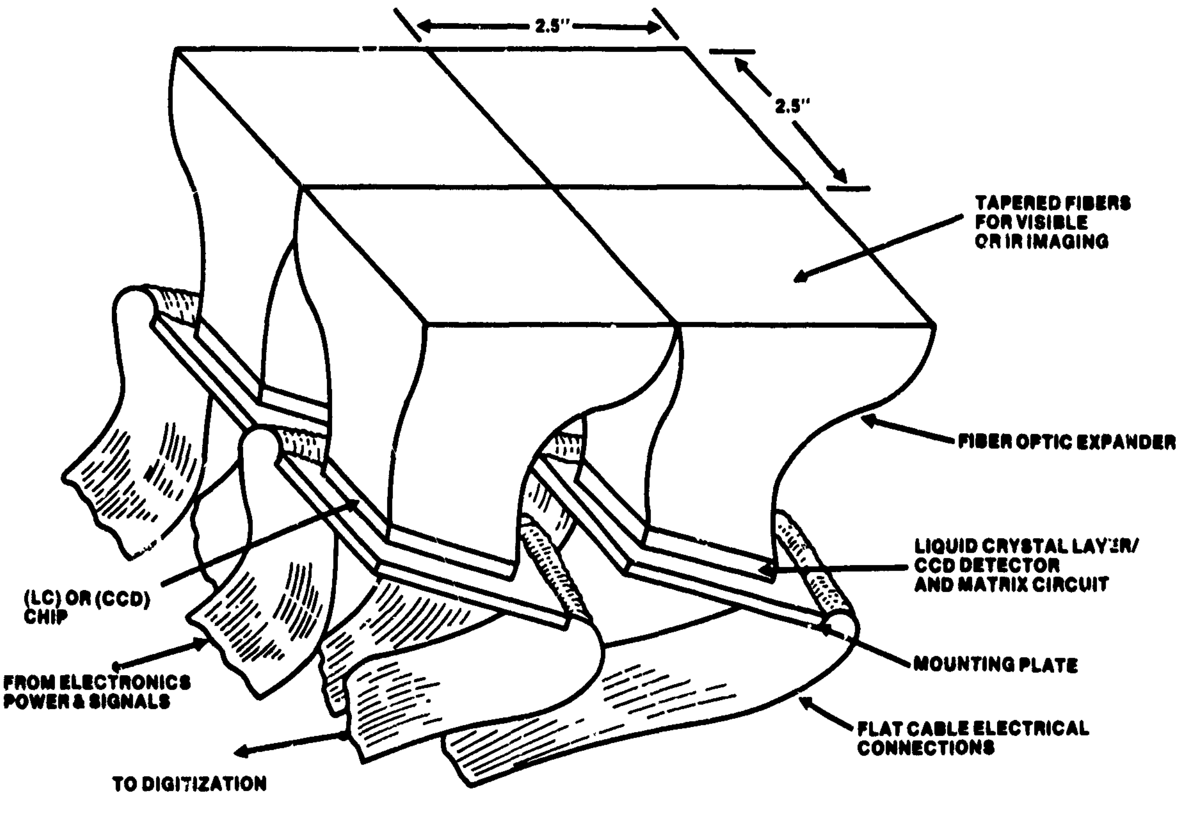

Fig.3.3.18 Fiber-optic wedges used to magnify and join four LC images into a single display

3.4 LARGE AREA GAS DISCHARGE DISPLAYS OR PLASMA DISPLAYS

3.4.1 HISTORICAL SURVEY

Undoubtedly the oldest electro-optical phenomenon able to produce light is an electrical discharge in a gas. Although this phenomenon is at the present time supposed to be at the origin of life on earth, millions of years elapsed until this effect was identified, analyzed and mastered by man. The "Paschen law" describing the discharge relationship (for a given applied voltage between two electrodes, the product of their distance multiplied by the gas pressure is a constant) dates only from the end of the 19th century (1889).

It is only in the early fifties that Kuchinsky developed a numeric indicator tube which became a standard for readout devices under the name of NIXIE. More recently, in the late 60's, other tecnniques began to replace it. In the NIXIE tube a single anode and a stack of separate cathodes, shaped in the form of numerals, are immersed in a gas mixture (3.4.1).

First attempts to produce a matrix display panel were made in 1954 (Skellet), the ignition of a discharge taking place at any intersection of two sets of electrodes. This technique was, however, limited to one cell at a time (3.4.2).

Since then, research has continued, the limiting constraining and contributing factors identified, and a host of different approaches have evolved.

All these are designated by the names of "Gas Discharge Displays" or "Plasma Display Panels" (P D P), the latter expressing the physical fact that when emitting light, matter is in its fourth state, made up of free ions and electrons.

Remark :

It will be noted that the vocabulary used in this chapter is not uniform. This results from the fact that ac and dc panels are not described by the same workers nor produced by the same manufacturers. Difference in vocabulary in most instances corrresponds to different concepts or data. In order not to confuse specialists of either technology, the most usual wording in each case has been kept.

3.4.2 GENERAL PRINCIPLES OF OPERATION

A gas discharge has several properties which are particularly appropriate for display applications (3.4.3). A neon discharge, for example, emits sufficient light for an attractive display with an efficiency of about 0.5 lm W^{-1}. Appropriately chosen gases emit ultra-violet radiation that can be used to excite phosphors as they do in fluorescent lights.

The gas discharge is characterized by an ignition (or striking or breakdown) voltage V_B (Fig. 3.4.1) above which an avalanche phenomenon takes place between the exciting electrodes and establishes the discharge with simultaneous strong emission of photons. As mentioned in 2.2.3, this threshold potential is of primary importance when the display consists of a matrix of cells. This self-sustained discharge is due to a space charge and high potential gradient at the proximity of the cathode. The I/V characteristic shows a negative impedance region, and the current is limited only by the series resistance. The discharge can be maintained with an applied voltage lower than V_B, down to a cut-off potential V_S where it extinguishes. On Fig. 3.4.2.a one can see the positive column, close to the anode and separated from the negative glow by the FARADAY zone. Fig. 3.4.2.b shows the potential distribution and Fig. 3.4.2.c the luminous intensity distribution (3.4.4).

Between the ignition V_B and extinction V_S voltages the cell can be either "on" or "off", depending upon the previous conditions and the arrangement : it can be used therefore as a bistable element (3.4.5).

In spite of this threshold, in multi cell arrangements unwanted cells with electrodes in common with "on" cells may also ignite. One reason for this ambiguous firing is that the glow discharges are low impedance elements which couple electrodes together. In order to avoid this coupling and to limit the flow of current, an impedance must be placed in series with each cell.

In 1963 Thompson (3.4.6) made a 10 x 10 array arrangement with one resistance associated to each cell, any of which could be selectively and concurrently turned "on" or "off". This was the precursor to dc gas discharge displays. In 1964 Bitzer and Slottow (3.4.7) realized that such an impedance could also consist of a capacitor. This prevented the use of dc since the discharge could not be maintained in the cell ; capacitive coupling is, however, compatible with ac. The ac plasma display panel was presented in 1966 (3.4.8). At present, gas discharge displays are indeed classed as ac displays or dc displays (3.4.9). Both can be operated in storage or non-storage modes, storage meaning that the memory is inherent to the display device, whereas in the non-storage or refreshed or cycling mode, an external memory is added to the display and the information is sequentially transferred and refreshed frequently enough to avoid flicker, like in any other "non memory" display.

3.4.3 AC PLASMA DISPLAYS

3.4.3.1 General description

Most manufacturers produce ac P D P's of various sizes operating on the principle described in 3.4.3.2.

Fig. 3.4.3 shows a cutaway view and a magnified cross-section of a large ac plasma panel intended to display a great number of characters or elaborate graphics. It consists of two identical glass plates (1) imprisoning a gas (2) in which the discharge takes place. The inside surface of each glass plate carries rows of parallel conducting electrodes (3) insulated from the gas by a dielectric layer (4), made of materials which must also satisfy specific requirements, such as resistance to sputtering by ionic bombardment, lowered firing voltage, etc... In general it is not possible to have these electrodes made of transparent conductive material (like Indium Tin Oxyde) due to the large surge current taking place when the discharge starts. The plates are assembled with their electrode networks orthogonal to each other and with a small uniform gap between them. In some realizations a matrix of holes in a thin plate was used to localize the cells but in most products this has been avoided and the cells correspond to the intersections of the two sets of crossed rows of electrodes. The gap is first evacuated and then generally filled with a neon-argon mixture which emits a characteristic red-orange luminescence with each electrical discharge.

3.4.3.2 Operating principle

In operation, a square-shaped ac voltage called the sustaining voltage is permanently applied to all X and Y electrodes : Fig. 3.4.4.a. (3.4.10). Its value is such that the electric field is not sufficient to initiate the discharge of the gas. In the absence of any other signal, the panel is in the "off" condition. Ignition of a cell, defined by the intersection of a line and a column is achieved by applying between them a writing signal, in the form of an auxiliary instantaneous voltage of proper phase exceeding the firing voltage, which initiates the discharge : Fig. 3.4.4.b.

The ions and electrons generated by this discharge will build up on the dielectric covering the electrodes creating an opposite potential ($-V_M$), and the actual potential across the gas will drop causing the discharge to be rapidly quenched. During the next half-cycle, when the sustaining voltage presents a reversed polarity, the potential of the walls has no longer an adverse effect, but on the contrary, will add to the sustaining voltage, so that the resulting voltage is then sufficient to exceed the firing potential. A new discharge will occur with corresponding electron and ion deposit and then extinguish again ; the adressed points (and only those) will continue to fire twice per cycle (once per half-cycle) of the sustaining voltage. The brightness will therefore be proportional to the frequency of the sustaining voltage, up to an upper limit, where there is no longer enough time for the charges to build-up on the walls and the memory effect no longer exists.

Extinction of a cell is achieved similary by applying a short pulse of the proper phase to the appropriate pair of X and Y electrodes. A short discharge Fig 3.4.4.b takes place which cancels the stored charges and hence the corresponding memory potential ($-V_M$). The next half-cycle of the sustaining voltage will find the cell as if it had not been previously "on", and cannot therefore ignite it.

In other words, the panel has an inherent memory and any point can be selectively written or erased.

3.4.3.3 Physical characteristics

The shape of the display using a PDP is mainly determined by the dimensions of the panel itself. The thickness of the panel does not exceed 2 cm and its overall and useful areas are essentially related to the pitch of the cells and to their number. However operating constraints (high surge current, wave shape changes along long connections which affect the operation, etc.) impose that most of the drive electronics be placed immediatly adjacent to the panel. The total thickness of panels with their drive electronics can be no more than 5 or 7 cm.

The front dimensions of panels (in these where there is no requirement for rear optical access) can be arranged so not to exceed the useful area by more than a few cm. Panels with 128 x 128, 128 x 256, 512 x 512, and up to 1,024 x 1,024 cells are available from different manufacturers with cell pitches ranging from 0.57 mm to 0.4 mm and with associated electronics allowing alphanumeric, semi-graphic, or full graphic addressing. The dimensions of these panels range from 10 x 10 cm up to 45 x 45 cm ; the number of pixels from 16,000 to more than 1.10^6 and in the alphanumeric mode a display capability ranging from some several hundreds to 20,000 characters.

The operating life of ac panels is very long, working hours in excess of 50,000 having been demonstrated. This is by far more than enough for military aicraft applications but, unfortunately, sacrificing on operating life would not provide a sufficient increase in luminance for much better legibility under the high ambient illumination that prevails in cockpits at high altitude.

The panels themselves are very sturdy and the associated electronics may be ruggedized without special difficulties. High altitude operation is made easier than for CRT's for instance, by virtue of the much lower voltages involved.

However, should the panel be exposed to low pressures, it would "inflate" due to the internal pressure of gas and some characteristics may change, resulting in erratic firing, or misfiring of cells. This effect however remains limited provided a proper design has been made.

The written information is stored without any need of "refreshing". The data input rate may be very low.

- Electromagnetic interference - Security. It must be noted that as in other devices where switching of rather large currents takes place, Electromagnetic Interference is produced. From the secrecy point of view, due to their acyclic type of operation, it is almost impossible to decode the data, and these panels compare very favourably with all other display media where the information is periodically refreshed or delivered through a fixed scheme (eg : TV raster ; "Self-Scan"dc panels mentioned hereafter) which may thus be easily deciphered. If stringent standards are to be met, special design of the panel and its drive electronics may become necessary. This problem has already been solved satisfactorily in France ; the remaining EMI, which is below most standards, is produced by the TTL circuits, rather than by the panel or its electronics.

3.4.3.4 Addressing, driving

The description of operation given above just mentions the main principles. In fact, the firing voltage and the "memory margin" vary somewhat from cell to cell due to manufacturing tolerances. On the other hand, although the frequency of the sustaining voltage is only about 50 kHz, the wave shape, the impedance of the source and the multiplexing technique used have a direct impact on the performance of the panel. The address circuits of most alphanumeric or graphic panels employ for multiplexing a network of two diodes and a resistor associated with each electrode plus high voltage driving amplifiers. This is still done (in 1981) with discrete components in association with integrated diodes and resitors, resulting in high cost. As in electroluminescence, with which there are common requirements, the difficulty of integrating stems first from the high voltage involved : 100 to 170 V or even more, are required for some driving schemes, values which at present are uncommon in integrated circuits. To a lesser extent it results also from fast switching requirements, driving capacitive loads with large surge currents and "totem pole" output etc...
Thirty two channel 40 leads IC drivers for plasma panels have been announced, but prices and reliability still remain unfavourable due to a complex manufacturing process which implies several different IC technologies. However, EPIFET and DMOS approaches appear to be very promising solutions, and work is underway in several countries (USA, France, Japan).

3.4.3.5 System interface

Due to the close inter-relationship between panel and drive electronics, and the highly significant part of the price that the latter represents, most manufacturers provide the user with a "display function" incorporating the panel and factory-set drive electronics, which can be made very compact and sturdy. The system electrical interface is then reduced to a power supply and some TTL signals. In a typical alphanumeric panel, for instance, these will consist of :
. "line" and "column" address of the character.
. ASCII code of the character
. Control signals : "Writing", "Selective erasure" or "Total erasure".
Graphic panels, of course, require more inputs.
Manufacturers offer a choice of panels with different sizes and organization : alphanumeric only, where characters may be written in a predetermined format (5 x 7 ; 7 x 9 ; 8 x 10 ; 10 x 10 pixels) ; graphic, where any element may be driven independently ; or semi-grahic, where elements may be addressed independently but in a predetermined "block" of pixels.

3.4.3.6 Visual characteristics

The most important visual feature of ac PDP's is the quality of the display. It is absolutely flicker-free thanks to the high supply frequency (2,000 times the eye's image fusion time, with two ignitions per cycle). Each point is perfectly located so that no distorsion occurs and the pattern remains steady and free from any jitter. Therefore, there is no noticeable fatigue of the eye even after a long observation time.
No image break-up or stroboscopic effect (temporal aliasing) (see glossary and ref. 1.10) occurs in the case of relative motion between the observer and the display as opposed to "refreshed" displays (CRT's, scanned dc plasma panels or certain electroluminescent panels).

The color orange is typical of the neon-argon gas mixture.

The available resolutions are already good enough to permit the display of alphanumeric or graphic data (0.4 mm pitch) observed from a typical distance of 40 cm without noticeable effect (spatial aliasing) resulting from the discretization ; this in accordance with the eye's characteristics. Large panels with increased resolutions (25 % : 0.3 mm pitch) have been designed and will be in production in the near future.

The viewing angle is very wide, close to 180° with a dip in luminance on the perpendicular to the panel. This is due, as for many matrix displays, to the presence of the column conductors on the front glass sheet which, even if transparent, partly hide the discharge.

Morever, by proper arrangement of the drive electronics, it is possible to give access to the rear face for the addition of data, either by projection on a matt finish, or through direct superposition, by taking advantage of the transparent nature of both constituting plates.

As the glass sheets are transparent and as no diffusing material is in contact with them (like phosphor in CRT's or electroluminescence), the contrast is good even on bare panels. It may be further improved by the addition of an absorbing material at the rear, and an anti-reflection coating.

There are, however, two shortcomings which restrict the use of these panels in a military aircraft environment :

The luminance is limited to 200 or 300 cd m^{-2}. This does not allow usage in demanding applications like H U D, although this may be sufficient for fuel management, area navigation, and of course, all crew compartment use.

Dimmability is limited to a ratio of 3 or 4 to 1. This dimming can be obtained by two ways, either by changing the sustaining voltage frequency, thus varying the luminance of the whole display, or erasing and re-writing selectively only a part of the display which gives "shades of grey".

Colour

No colour ac PDP's are available industrially although the feasibility of multichrome panels has been demonstrated (3.4.11)-(3.4.12)-(3.4.13). In the multichrome approach, sets of three properly located pixels (trios or stripes) are coated with different phosphors, and the sensation of hue results from the addition, within the eye, (section 2.4.1) of the three stimuli so obtained in the very same way as in a shadow-mask CRT. The price paid for colour capability is a drop in resolution, since three luminescent sites are used to present one perceived element.

In a similar way, monochrome displays with different colours from the neon-orange (eg. green) can be made where a single phosphor is used. In both instances the gas mixture is generally replaced by xenon, which yields a higher U.V. content, which in turn improves phosphor excitation. However, unless cells are defined by holes in a non U V transmitting material, and indexed with electrode crossings, optical crosstalk can take place, these two reasons cumulating to make it difficult to achieve good resolution in colour.

3.4.3.7 State of development

Invented 15 years ago, ac panels have only recently been extensively employed.

First uses were found in non-military applications, like the PLATO automated teaching system, for which they were indeed first designed, and banking and air traffic control terminals. They are finding widening acceptance in the military field, mainly in command and control functions, such as in US Submarines ; US Navy's DIFAR ; US Army's DIVAD and SST ; MIFASS program (Marine Integrated Fire and Air Support System) ; the French ATIBA (artillery control) system and the UK PTARMIGAN program, and in several Electronic Counter Measures (ECM) systems.

They are generally used in the alphanumeric mode, although in some applications provision for semi-graphic or even full graphic addressing is made allowing cyrillic, arabic or kana characters to be displayed, together with symbols and drawings. All of these may be superimposed on a map placed at the rear face.
No pictorial TV-like applications are known to be under consideration.
Once again, the limitations do not come from the panels themselves, but rather from the associated electronics. Attempts have been made actually to produce animated TV-like pictures with several shades of grey, one of the most promising approaches being based on the "dithered order" principle (3.4.14) - (3.4.15).
To summarize, one can say that at present, ac panels with dimensions of up to 45 cm (60 cm diagonal) are available and up to 1 m wide have been demonstrated (3.4.16), panels with resolutions of 0.3 mm (83 l/inch) will be available in the very near future and up to 0.25 mm have been demonstrated, alphanumeric and graphic displays without half-tones are common-place, military environment extremes are, or can be fulfilled, and colour and full image characteristics have been demonstrated and can be produced at the expense of a complex electronics which remains the weak point of ac PDP's until high voltage integrated circuits (convenient for both plasmas and Thin Film Electroluminescence) are themselves available. Luminance remains a limitation.

3.4.4 DC PLASMA DISPLAYS

3.4.4.1 General description

Most of what has been said for ac plasma displays applies to dc plasma displays. The major differences with the description of the former, given in 3.4.3.1, are that the electrodes or resistive extensions thereof are directly immersed in the gas mixture, and that in most cases, it is necessary to add a stencil plate. The holes of stencil plate are registered with the crossing of the electrodes and thereby localize the cells. This is generally necessary to limit the consequences of electrodes sputtering by ion bombardment, or for separating the display discharge from the transfer discharge (see below). This obviously adds to the difficulties in manufacturing the panel.

3.4.4.2 Operating principle

Various principles can be used to operate dc gas discharge panels, but basically they are supplied with a unidirectional voltage, either pulsed or sustained, the latter giving the memory mode (3.4.17)-(3.4.18)-(3.4.19)-(3.4.20).
Individual cells are struck on by application of a voltage pulse in the range 150-200 V. As soon as a stable discharge has been established, the cell impedance drops significantly, and it is therefore necessary to provide a series resistor to limit the current flow in the cell. Most commercial matrix panels are multiplexed in the pulsed mode and because only one line of the display is addressed at any one time, it is only necessary to provide a resistor in series with each column driver. This drive technique, however, yields a rather low brightness (150 cd m^{-2}). Where high display brightness is required, as in the aircraft cockpit, it is necessary to operate the display in the memory mode, in which an addressed cell is active for almost the whole of the frame time, thereby yielding a much higher mean brightness. The memory effect is achieved by striking a cell on, as described previously, and then reducing the voltage to a level high enough to sustain the discharge but too low to ignite adjacent cells. The main disadvantage with this drive scheme is the necessity of a limiting resistor in series with each individual cell in the display.
The difference between the strike voltage and the maintaining or sustaining voltage is known as the working margin. The spread which occurs in these two panels voltages due to the manufacturing tolerances presents a further difficulty for memory operation.

Degradation of the working margin results in non-uniform operation across the display.
A third problem is the statistical time lag between application of the trigger pulse and the establishment of a stable discharge in the cell - an effect known as jitter. This poses no difficulties for the ac plasmas thanks to the high frequency of the sustaining voltage but does pose problems with operation in the memory and the pulse modes of dc plasmas. In order to minimise jitter, it is necessary to prime the cells by introducing ions or electrons into the cell, prior to the application of the strike voltage. This is normally achieved by incorporating priming cells into the panel in close proximity to the data cells. The priming cells are blanked from view, so that their light emission cannot be observed. The priming effect, which is the ability to use one discharge to affect a neighbouring site, and thus manipulate the position of the discharge, is unique to gas discharge displays. Fig 3.4.5.a illustrates how the striking voltage V_B varies with the distance from an active site : the closer they are the lower V_B is. Therefore, by just using a three phase voltage variation applied on scan electrodes it is possible to shift the discharge from cell to cell: Fig 3.4.5.b. This principle is used in the device known as the "Self-Scan" R.

Fig 3.4.6-(3.4.21)-(3.4.22). At some cost in the panel complexity, this device exploits glow priming and transfer techniques to provide considerable reduction in circuit complexity and cost. An exhaustive description of this device may be found elsewhere (3.4.9).

The priming effect is also used in a device more recently described, able to display several lines of 80 characters and intended for small basic word processors (3.4.23).
The self-scan mode, however, suffers several limitations regarding display size, brightness and number of displayed elements, which restricts its application mainly to cash registers and banking terminals. In order to simplify the electro nics, these panels are activated by a multiplexed scanning signal along the rows and columns of the matrix. The frame scan must exceed about 50 Hz and a row cannot contain more than 300 dots, otherwise flicker becomes quite noticeable and the display dims. Therefore, these panels are limited to purely alphanumeric display of about forty 5 x 7 pixels characters per row. To overcome some of these limitations, a modified type of operation has been described (3.4.24), recently combining ac 16.7 kHz operation for memory display and "Self-Scan" dc drive.

Fig 3.4.7 is a cutaway view of the design, and Fig 3.4.8 shows the wave forms for the different voltages.

A thin metal plate with holes in it, called the priming plate, separates the discharge space into a front memory section operated in the ac mode, and a rear, dc operated, scan section.

The front plate is coated with a transparent continuous conductive layer, itself coated with an insulating layer. The stencil priming plate is also covered with an insulating layer. The result is that all cells in the memory layer are connected in parallel. Each cell is isolated from its neighbors by the glow isolator mesh. These two insulator covered plates, when fed with an ac voltage pro-vide the memory capability. Scan anodes are located at the bottom of grooves in the rear plate. Six phase cathode wires can be seen in the figure 3.4.7, orthogonal to the anodes and isolated from the priming plate by glass stripe spacers. Operation of the scan section is similar to that of earlier refresh type "Self-Scan" displays, except that scan is initiated only when changes are required in the display content.

This configuration claims to allow the display of over 96 characters per row without flicker, with improved luminance and multiplexing possibility which reduces the number of address lines to about one tenth of those required to address each pixel. It has still to be demonstrated that this economy is large enough to balance the added cost in manufacturing the panel, and whether this design might be compatible with displays, other than alphanumeric.

3.4.4.3 Physical characteristics

The front dimensions of dc PDP's together with the associated electronics, do not significantly differ from the useful area, as is indeed the case for ac panels and their thickness is also in the order of several centimeters.

- The commercially available panels have a display capability from 1 row of 16 characters up to 12 rows of 80, while an alphanumeric and limited graphic unit contains 17 lines and 192 columns. A panel of 128 x 128 elements has been reported. The number of characters then ranges from 96 to 960 and the overall length is around 30 cm.
- The poor resolution results from the coarse pitch (0.75 mm horizontal ; 1 mm vertical). This may be considered adequate for alphanumeric character display but is unlikely to give sufficient resolution for vector graphic display. Further development of the technology to provide finer pitches is likely to be limited by the mechanical tolerances of the panel components, cross-talk caused by the close proximity of adjacent cells, and by tolerances in the resistor arrays. It is therefore unlikely that a pitch below 0.4 mm could be achieved, limiting the resolution over large areas to 25 lines per cm.
- The operating life expectancy is 30,000 hours under normal conditions. However this can be drastically impaired (to, say 100 hours) for panels operating below 10°C, and which contain mercury, as it is usually the case for dc panels ; and for these at least, no operation at all is possible below 0°C. The Hg vapor in the gas mixture is necessary to avoid sputtering of electrode material. At low temperatures, the Hg protective effect is greatly reduced, therefore bringing about an increased rapidity in electrode deterioration.

3.4.4.4 Addressing - Driving

As has been seen in paragraph 3.4.4.2 there are several different ways for operating dc panels, and the requirements are more closely related to the panel design, than for ac ones. Therefore the vast majority of dc panels are supplied with the drive electronics (except perhaps for some single character-row types) and the interface is reduced to supply and logic.

3.4.4.5 Visual charateristics

- As in all other matrix displays, the picture is distortion free and each element is precisely located.
- In most designs, holes in a stencil sheet define the cells. If the cathode, and hence the discharge, is not located on the front surface (or on top of the hole) the viewing angle may be lower than for ac panels, not exceeding a cone of 100° to 120°.
- The colour is neon-orange or green, the latter being obtained by the use of suitable U.V. activated phosphors. The phosphors are coated onto the cell walls and are activated by the U.V. emission in the gas discharge, in which case Xe is incorporated in the gas to enhance U.V. emission. Several manufacturers market displays incorporating phosphors which emit in the green. This however, further restricts the viewing angle, and produces a colour shift from green to reddish yellow and red when changing from the orthogonal to the lateral viewing position. A matched green filter should obviate this effect, and since the contribution from the glow to the total luminance is small, the reduction in luminance should be small too.
- The major pitfall of these panels when operated in the pulse mode is the flicker, (which imposes a refresh frequency of typically 70 Hz, thus limiting the number of cells per line as mentioned) and a display "break-up". This is particularly true for panels with no phosphor coating but, in spite of the decay time added by phosphors, it remains objectionable to dc panels where such a coating is used.
- The luminous efficiency (0.5 $\mathrm{lmW^{-1}}$) yields a mean pulse mode driven panel luminance in

the range of 100-150 cd m^{-2} which, as stated previously, is inadequate for good legibility in conditions of high ambient illumination. Some panels, which are pulse driven, have a quoted mean brightness of 60 to 100 cd m^{-2}. For very high brightness displays, memory addressing techniques are used, as described for example by Smith (3.4.12) who quotes operation at luminance levels up to about 3,000 cd m^{-2} with an experimental display. The panel can be operated at a luminance as high as that found in CRT's, but the current density required to do this involves excessive sputtering of the cathode material, and the life of the panel is significantly reduced.

Panels displaying 7 rows of 15 characters each having a 7 x 5 format, which can be operated in the memory mode at up to 1,000 cd m^{-2} have been produced. The basic inefficiency of the discharge mechanism, combined with energy dissipation in the series resistors, means however that considerable heat is dissipated at these high luminance levels. In the long term, the dc gas discharge panel does not appear to be as promising for aircraft use as the thin-film EL panel.

- Dimming

A dimming ratio of 5 : 1 for the "Self-Scan" displays has been quoted, but because of the visibility of the scan-glow, legibility in dark environments is impossible. It is desirable that panels for aircraft cockpit be sufficiently bright to be legible under 100,000 lux and should have a dimming ratio of 1,000 : 1. Drive circuits for high brightness panels have been developed in the U.K. which enable dimming ranges greater than 500:1 to be achieved.

3.4.4.6 State of development

Existing dc plasma panels have been specifically developed for the display of a few hundred alphanumeric characters, and have found applications mainly in bank teller's terminals, industrial process management, etc... There are at present no commercial panels suitable for the display of vector graphic information, and significant further research may be needed to provide the fine pitches necessary. Little work has been published on the performance of matrix addressed dc plasma panels over the full military environmental range. It is not anticipated that there will be any problems caused by vibration specification of panels operating in military aircraft cockpits which are not fully pressurised, and it would be necessary to control temperature as mentioned.

The brightness of displays presently available from the two major manufacturers of dc panels is inadequate for full sunlight viewing, but it is hoped that panels under development will have sufficient brightness while maintaining the characteristics of life expectancy and temperature independence.

The US Army has been employing the "Self-Scan" in Digital Message Device development models, and a panel of 7 rows of 15 characters is used in the flight management system of the Lockheed 1011-500 commercial aircraft. Provided suitable contrast enhancement techniques are applied, reasonable legibility may be obtained under 100,000 lux ambient illumination, as met in a military aircraft cockpit at high altitude.

Studies have been carried out in order to develop colour TV plasma panels, by using dc structures in conjunction with photoluminescent materials. In general these devices use positive column discharge which allows a better luminous efficiency necessary for TV pictures presentation without excessive power consumption. Nevertheless, none of these studies have reached the commercial stage.

To summarize, dc PDP's have up to now been produced for non military, alphanumeric applications with limited size, number of characters, and low resolution. Although they have the inherent capability of displaying half-tones, this seems to have been little employed. Their high brightness capability in the memory mode may be hindered by life expectancy problems, particularly at low temperature, and heat dissipation.

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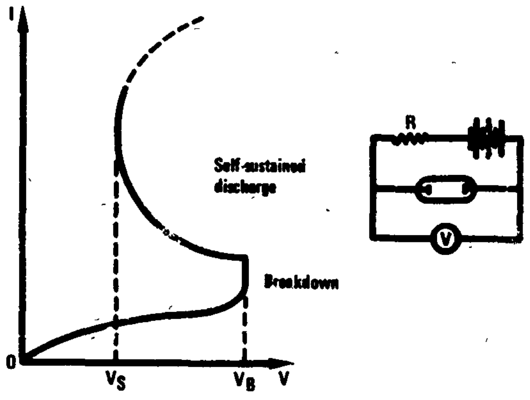

Fig.3.4.1 I=f(V) characteristics of gaseous discharge

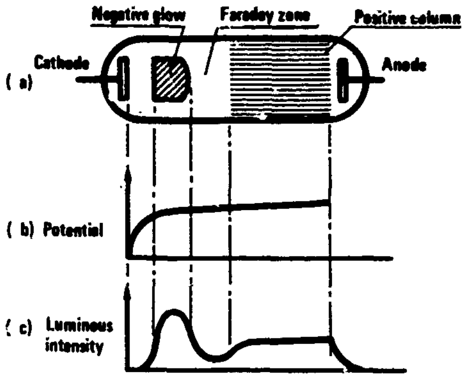

Fig.3.4.2 Gas discharge: potential and luminous intensity

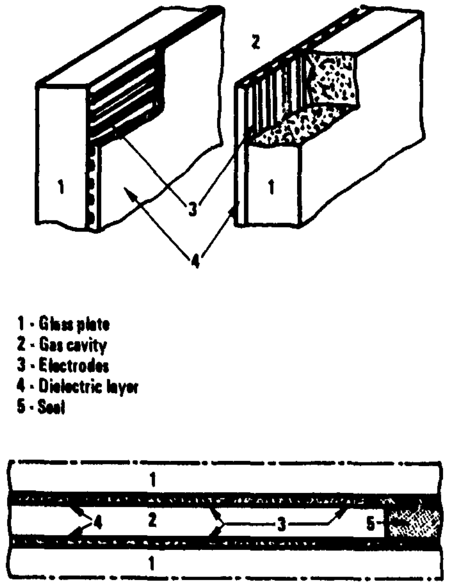

Fig.3.4.3 AC plasma panel structure

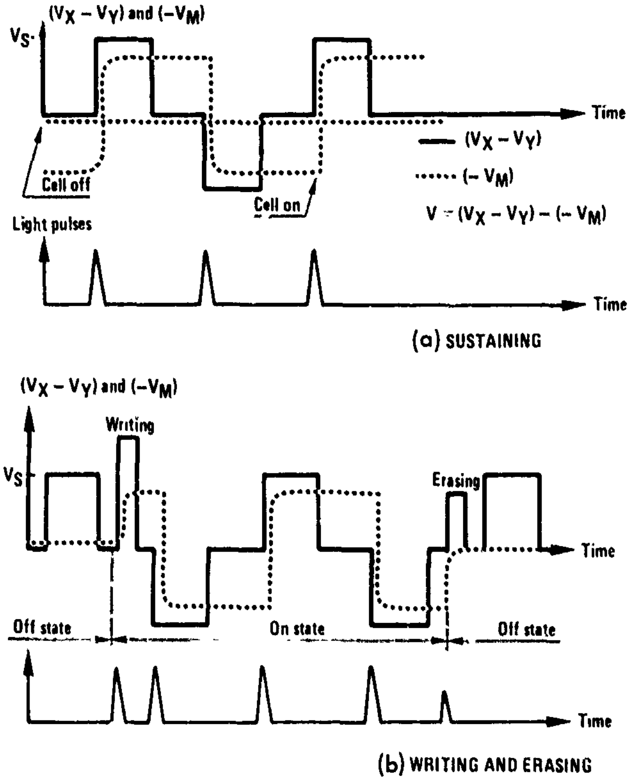

Fig.3.4.4 Sustaining, writing, erasing voltages wave forms

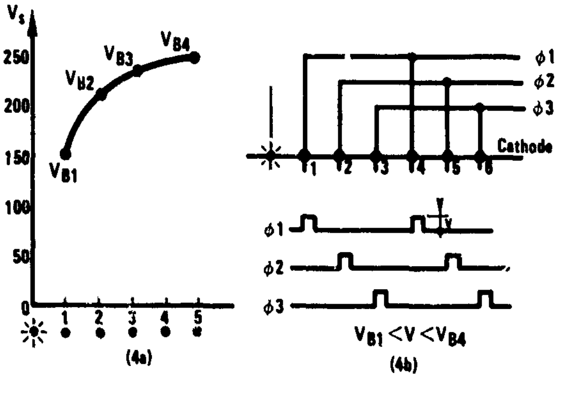

Fig.3.4.5 Priming and shifting mechanism

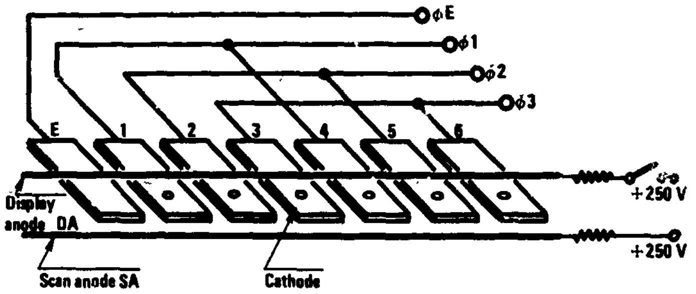

Fig.3.4.6 Self-scan schematic structure

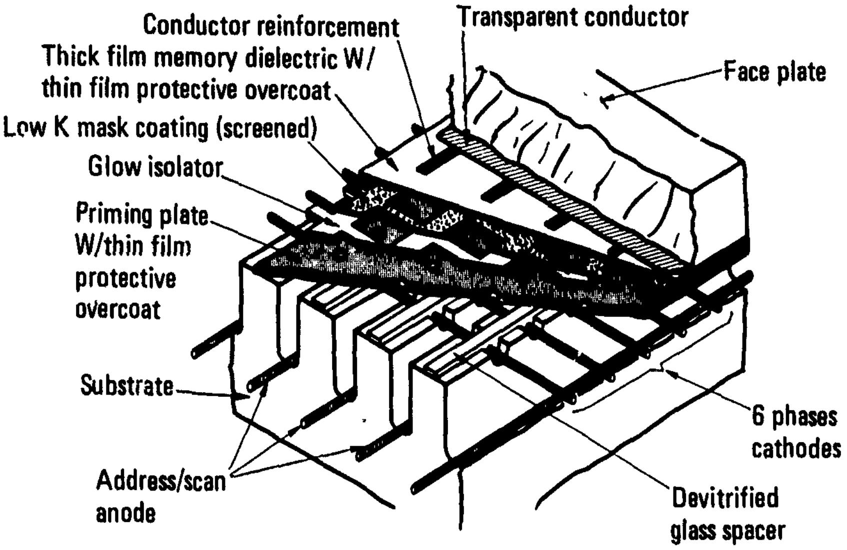

Fig.3.4.7 Cutaway view of the self-scan memory display panel

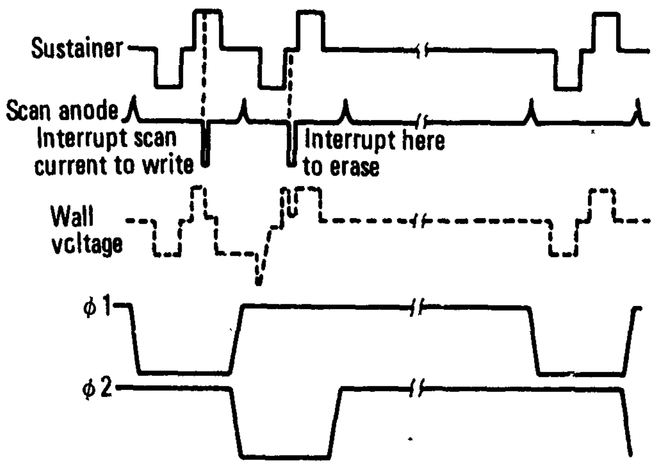

Fig.3.4.8 Typical addressing waveforms and the resulting memory cell wall voltages

3.5 LIGHT EMITTING DIODES

3.5.1. INTRODUCTION

The evolution of Light Emitting Diodes (LEDs) started in the 1950's as a result of the initial search for materials suitable for the formation of improved quality diodes and transistors. A low efficiency yellow emitting silicon carbide device using an insulated metal contact to inject electrons had been demonstrated in the 1920's but its development was not pursued. The start of the 1970's marked the first real attempts to apply the research which had been conducted to the development of practical LED display devices suitable for airborne applications.

Any semiconductor having an energy band gap wide enough to support a visible radiative recombination process is a potential candidate for the fabrication of LEDs. Materials used successfully for the formation of light emitting diodes include SiC, a compound of Chemical Group IV elements, several Group III-V compounds and several Group II-VI compounds. Extreme difficulties experienced in forming pn diode junctions within Group II-VI compounds resulted in the development of a metal-insulator-semiconductor electron injection structure that to date has in general been characterised by relatively low light emission efficiencies.

Group III-V compounds turned out to be suitable for the formation of relatively efficient pn junction type LEDs. Commercial LED development was initially restricted almost exclusively to the high market volume red LEDs, with a more recent expansion into the orange, yellow and green colours, which can also be made using the GaAs/GaP system. The potential for efficiency improvements in most types of III-V compounds LEDs still remains relatively good, (ie. LEDs use high dislocation density substrates and are not optimised optically) however, a commercial product incentive for making these improvements is lacking since present devices are satisfactory except for the aircraft and military market.

In spite of the development limitations just described, LEDs have reached the point where they are being successfully applied to airborne numeric and alphanumeric display tasks with more sophisticated graphics displays designed for aircraft installation nearing completion.

3.5.2. PRINCIPLES OF OPERATION

The physics of LEDs has been the subject of a number of text books in recent years and will be dealt with only briefly here. Basically, photons are generated in a semiconductor when an electron associated with the conduction band recombines with a hole associated with the valence band. This is a non-equilibrium process and is most easily effected by injecting minority carriers across a forward biased p-n junction. To a first approximation the energy of the emitted photon is equal to the energy difference between the initial electron and hole states and must lie between 1.9 and 2.7 eV for the photon to be in the visible region of the spectrum.

The efficiency of the radiative recombination process depends on various parameters, the most important of which are detailed band structure and crystal perfection. Solid State theory predicts irradiances much greater for direct gap semiconductors than for indirect gap semiconductors. GaAs has the required direct gap band structure but its energy gap of 1.44 eV corresponds to near infra-red radiation. GaP has the required energy gap of 1.26 eV for green radiation but has an indirect gap. However, these two compounds are completely miscible throughout the ternary composition to form a range of alloys $GaAs_xP_{1-x}$. The different types of energy gap band structure and alloys with larger phosphorous content have an indirect band structure. Diodes made from an alloy composition close to this cross-over point exhibit deleterious inter-band carrier transfer effects and optimum radiant efficiencies are obtained at x=0.4, which corresponds to the red displays familiar (once) in pocket calculators and digital watches.

The argument outlined above on radiant efficiencies relates to recombination processes associated with free carriers or shallow donor and acceptor levels. In indirect gap alloys in the $GaAs_xP_{1-x}$ system the efficiencies may be increased by the use of nitrogen as an isoelectronic trap. Nitrogen, being a Group V atom, should not be electrically active but the large difference in its electronegativity and convalent radius over those of the arsenic or phosphorous atom it replaces in the lattice creates a shallow trap close to the condution band edge. Once an electron is bound in this trap the centre becomes negatively charged and can readily capture a hole in the long range coulomb potential to form a bound exciton, which decays with the emission of a photon. This process results in more than two orders of magnitude increase in efficiency for green GaP radiation at 565 nm than when nitrogen is not present. If nitrogen is in the lattice in excess, excitonic recombination at N-N pairs shifts the peak wavelength into the yellow region of the spectrum at 575 nm. A similar process, involving the "molecular" Zn,O isoelectronic trap is responsible for the extremely efficient red emitting devices made in GaP.

It is difficult to prepare large bulk single crystals of the ternary alloys, and devices are made in epitaxial layers grown on either GaAs or GaP substrates, depending on the precise alloy composition required. Since the lattice constants of these two compounds are significantly different it is first necessary to grow a graded layer in which the initial composition is that of the substrate, and in which the phosphorous content is gradually increased until the desired alloy composition is reached. A layer of constant composition is then grown. The crystal perfection, and hence ultimate device luminescence efficiency, is a function of both the graded and constant composition layers. This explains the large differences in efficencies reported for commercial and laboratory performance of devices, where the latter use more careful prepared material. A summary of the range of efficiencies is given in Table 1. When corrected for the response of the human eye, the green 565 nm (0.3% efficiency) commercial LED has a luminous efficiency of about 1.9 lm W^{-1} as compared to 0.5 lm W^{-1} for the 640 nm red and 0.06 lm W^{-1} for the 698 nm red commercial devices.

Junction depths vary in the range 1-3 μm for direct gap alloys and in the range 5-25 μm for the indirect gap material. Slice processing is completed by depositing, delineating and alloying suitable ohmic contacts to the p- and n- regions of the devices.

The desired display format may be achieved with LEDs either by monolithic or hybrid construction. In the former case the format is obtained by diffusing the diodes into a single n-type substrate, which acts as the common cathode, and bringing out contacts for connecting the individual anodes to the address circuitry. In the latter case slices are diced into discrete diodes which are mounted and bonded in the required pattern onto a thin or thick film circuit board, which in most cases also contains the address and drive electronics.

In either type of display it is important to maximize the contrast ratio by eliminating visible optical cross-talk at distances of one LED or greater from the activated diode. Cross-talk out to the imaginary boundary separating adjacent LEDs is actually a benefit since it increases the area averaged (ie. perceived) luminance of the picture element. Photons are generated isotropically across the p-n junction and, unless there is a high

TABLE 1

Efficiences of various LEDs

Colour	Wavelength (nm)	Material	Commercial (%)	Laboratory (%)
Green	565	GaP:N	0.3	0.7
Yellow	585	$GaAs_{.15}P_{.85}:N$	0.05	0.15
Red	640	$GaAs_{.35}P_{.65}:N$	0.3	0.5
Red	660	$GaAs_{.60}P_{.40}$	0.2	1.0
Red	698	GaP:Zn,O	2.0	12.6
Red	660-670	GaAlAs		1.0

internal self absorption, those travelling through the bulk will be emitted through any convenient window for which the angle of incidence is less than the critical angle. In direct gap LEDs (eg. $GaAs_{0.6}P_{0.4}$) the high absorption coefficient for the emitted radiation, particularly within the graded layer, eliminates virtually all optical coupling and only the surface of the addressed diode lights up.

Although high optical crosstalk might be considered a likely consequence of the emitted photon transparency of indirect band gap LEDs, the optics of the monolithic chip geometry instead predicts that virtually no optical crosstalk should occur. The large refractive index of indirect band gap LEDs causes the critical angle to define a very small cone (ie. 34° included angle for unencapsulated GaP) through which light reaching a surface can be emitted. Due to this emission angle restriction a perfect monolithic chip with parallel surfaces could only exhibit optical crosstalk for multiple reflections of those photons which are initially emitted within emission cone windows (ie. symmetric about normals to the display surface) which have apexes located within the LED junction area. All other emissions would experience total internal reflections. The Fresnel reflections within the emission window would result in a very rapid decay of luminance with distance from the LED junction edge and visible crosstalk on the chip's planar surface would be absent. The majority of photons are emitted outside the emission window and would eventually reach the monolithic chip edges where some would be emitted but most would again experience total internal reflection. LED emissions viewed microscopically through untreated LED chip edges do in fact allow the image of the LED junction to be observed.

In practice, well made indirect band gap LED monolithic chips perform as described above with one major exception. The bulk GaP substrates are far from being perfect crystals and as a result light scattering into the LED emission cone occurs both within the bulk crystal and at its unpolished surfaces. In a darkroom lighting one LED will cause the entire monolithic chip to illuminate at a low luminance level. Under normal cockpit display contrast, optical coupling 200 μm from the edge of an energised LED is no longer visible. The measured optical coupling distances of the indirect band gap LEDs would pose a potential image quality problem for video displays having resolutions much in excess of 50 LEDs/cm.

LED monolithic arrays intended for use in dedicated display formats can, at the design stage, be layed out in virtually any desired geometric configuration. More general display surfaces are obtained using matrix addressable arrays in which the anode and cathode connections are orthogonal to one another.

The most difficult issue encountered in fabricating good monolithic LED arrays is achieving diode electrical isolation. Anode isolation is readily achived since the diode junction of unaddressed LEDs are reverse biased when the addressed LED is energised. Several approaches have been used to obtain the more difficult cathode isolation. A truly monolithic process, analogous to that used in silicon integrated circuit technology, has been demonstrated in monolithic chip sizes of up to 12.5 cm square. The technique requires special epitaxial material and a complex processing schedule involving both deep and shallow diffusions. The objectives of the research, which centred on achieving cathode isolation and a flip chip electrical connection structure, were fully achieved. Further research on this LED structure is being conducted to improve it from a 25 to 50 pixel/cm resolution. The major advantage the technique will offer when fully developed is an unobscured viewing surface, since both the cathode and anode connections are made on the rear side of the monolithic chips. The latter feature is highly desirable when used for the construction of mosaic display surfaces based on the four edge abuttable LED display module technique described elsewhere in this paper.

An alternative display fabrication technique which has been in use now for over ten years involves conductive epoxy bonding monolithic LED array chips to a thermally conductive electrically insulating substrate. The isolation is then achieved using a precision mechanical saw that cuts through the complete semiconductor slice and the gold surface layer on the ceramic substrate carrier. Connections to the anode rows are made either by stitch bonding or beam leading. This technique has been used with success to fabricate small single and multicolour non-abuttable arrays with resolutions up to 50 pixels/cm. It has also been used for constructing large area LED displays at a 25 pixel/cm resolution.

A third fabrication technique involves the hybrid assembly of discrete LEDs using automatic die placement equipment. This approach has also resulted in successful matrix arrays up to 25 pixels/cm resolution. Luminance outputs of 17×10^3 cdm^{-2} are typical of recent GaP material (3.5.1) at drive currents of 0.03A mm^{-2} leading to contrast ratios over 4:1 in sunlight.

3.5.3. PHYSICAL CHARACTERISTICS

3.5.3.1 Luminance Characteristics

Light emitting diodes produce a luminance output which is roughly proportional to the current density passing through the forward biased LED junction area. The current required to produce a desired luminance level is therefore directly proportional to the size (ie. junction area) of the particular LED being illuminated, and is the quantity which has to be controlled when using a LED as a display device. The forward biased voltage drop across a LED establishes the minimum supply voltage level needed to operate the LED (typically from 5 to 8V with voltage drops up to 3.5V) and also determines the power efficiency of the LED/driver circuit combination.

Nonlinearity in the LED luminance versus current characteristic is introduced by two effects: junction temperature induced efficiency (and colour) changes and current density induced luminance saturation. Both of these effects can result in a drooping characteristic. The temperature rise produced by the current flow is determined by a large number of thermal design factors which can vary significantly based on the layout, materials and fabrication techniques used in the construction of a specific display. The thermal conductivity of the LED array substrate, the electrical and mechanical bonding techniques used to affix the LEDs to it, and of the ceramic/heat-sink interface are particularly important if current magnitude induced non-linearities are to be minimised.

In the family of LED materials described by the chemical equation $GaAs_xP_{1-x}$, as the fractional composition, x, of arsenic increases, both the junction temperature and luminance saturation induced non-linearity effects in the luminance versus current characteristic become more pronounced. Green 565nm GaP (ie. with x=0) typically exhibits a luminance characteristic which is linear in current from very near its maximum saturated luminance to near luminance extinction (ie. linearity has been tested down to 3.4×10^{-3} cd m^{-2} but based on LED theory should continue to decrease thereafter in a linear fashion). A junction temperature rise in a GaP LED causes a linear decrease in luminance in the $-40^{\circ}C$ to $+125^{\circ}C$ temperature range of nominally 0.8% $^{\circ}C^{-1}$ and a 0.12nm $^{\circ}C^{-1}$ shift in the emission spectrum toward longer (yellow) wavelengths. As the arsenic concentration in the $GaAs_xP_{1-x}$ compound LEDs is increased the non-linearity of the luminance versus current characteristic becomes more severe at high current levels with saturation occurring gradually over a larger range of currents as the maximum luminance is approached. Red(655nm) $GaAs_xP_{0.4}$ exhibits a luminance decrease of greater than ten times that of GaP and a colour shift of 0.2nm $^{\circ}C^{-1}$ (nearly twice that of GaP) as the junction temperature increases. It should be noted that all of the preceding temperature sensitivities are only nominal values and will vary somewhat depending on the fabrication techniques employed.

3.5.3.2 Luminance Control Options

The nearly linear luminance versus current characteristic of LEDs, particularly at low luminance values, allows current amplitude dimming of LEDs to levels well below the 0.2cd m^{-2} level desirable for night flying or the 0.04 level needed for use with night vision goggles. The practical problems encountered with achieving these dimming levels in actual aircraft displays are those associated with implementing a current source control circuit design that is capable of handling a dynamic dimming control range of from 2,500 to 30,000 (depending on the type of display application) while continuing to look like a current source to the LEDs. A dimming control implemented to accept a digitally encoded input would for instance have to be capable of using a 16 bit binary luminance control word to avoid the perception of luminance changes as steps at the low end of the control range. Failure of the drive circuit to perform as a current source during dimming can result in luminance uniformity problems since the variations present in the knee region of the LED voltage-current characteristics can then influence the luminance produced by the LED.

The medium to low nanosecond luminance response times of LEDs also allow either or both linear pulse duration and linear pulse frequency control of LED luminance to be achieved. The response times of typical silicon integrated circuit logic and driver circuits serve as design limitations on the linear dynamic dimming ranges that can be achieved using these LED luminance control techniques.

3.5.3.3 Geometric Configuration: Small Area Displays

In small area displays, there are virtually no restrictions on the geometric configurations in which LEDs may be employed. Numeric readouts, bargraphs, scales, reticles, special geometric figures and small dot-matrix arrays can be fabricated and packaged to meet military specification environmental requirements.

At resolutions of up to 25 pixels/cm, hybrid LED arrays have been successfully formed using both semi and fully automated single diode placement and bonding techniques.

An alternative technique which has proved to be satisfactory for display resolutions between 16 and 50 pixels/cm is the manual placement of monolithic array LED chips. The chips, which typically have edge dimensions from 3 to 12.8 mm,, are abutted to one another in a mosaic fashion on high thermal conductivity substrates so as to produce the desired uninterrupted resolution across the entire display surface area and are then saw cut isolated and bonded. Both construction approaches have been used to produce military specification qualified LED arrays, with the monolithic approach used at resolutions of up to 46 pixels/cm, for HMD and film annotation applications.

As is the case for virtually all electronic displays, the overall design of a LED display system must be carefully optimised to produce a result that will be considered satisfactory by a pilot. In the case of LED head-down direct view displays, this requires that special attention be paid to the optical filtering, the electrical drive/address techniques employed and to the thermal design.

Overall display system design optimisation is equally critical when attempting to employ a LED display as an image source for a helmet mounted display application. (See section 3.5.7.2). In this case heat dissipation, weight and volume impose design restrictions. In addition, the luminance required of the image source is critically dependent on a variety of design factors only indirectly related to the LED. These factors for instance include: the image combiner field of view, the exit pupil size, the quality of the image combiner narrow band interference filter (which reflects the LED light with minimal blockage of the background scene), the transmittance of the high ambient light visor, and the scene luminance level when the pilot changes to the clear visor.

3.5.3.4 Geometric Configuration: Large Area Displays

The low operating voltages associated with dot-matrix LED displays require that increased average drive currents be used if the displays are to be operated at the same power levels as other higher voltage displays. Short low-resistance current leads are therefore necessary to minimise lead losses and to provide the near negligible voltage drop, between the LED drivers and the addressed dot-matrix picture element (pixel), that is required to produce displays which have a uniform luminance distribution across the entire surface. The method used to achieve this objective and still be able to have large-area LED head-down displays is to form the display surface using a mosaic of edge abuttable independent display modules, each having its own set of integrally mounted drive and address integrated circuits.

The first successful large area LED graphics display to be constructed using the modular building block approach was completed in 1978 (3.5.3). The display has active area dimensions of 10.4x7.8 cm and consists of four green emitting two-edge abuttable LED modules mounted side by side to form the display surface. Each module consists of a ceramic substrate of the same width as the LED surface but 13.3cm long and 0.1cm thick with a nominal 25 pixel/cm green emitting LED array of 2.6x7.8 cm dimensions centred on the ceramic and having its column driver hybrid integrated circuits mounted on the rear surface. The objective of this display was to allow evaluation of the feasibility of integrating the LED, optical filter, ceramic, metallurgy and silicon integrated circuit technologies required to build modular LED displays suitable for use in portraying real-time flight control information to a pilot. Based on the success of this concept demonstration display, a programme was initiated to develop flightworthy graphics displays utilizing a full four-edge abuttable module.

Figure 3.5.1 is a photograph of a green emitting, nominal 25 pixel/cm resolution, GaP LED display module. A heat sink serves as the basic structural element for the module to which the LED display surface ceramic substrate, driver substrates, connectors and a power line filter capacitor are solidly attached. The display module is a cube having about 2.6 cm edge dimensions. The modules are designed to permit their individual removal or replacement in the display mainframe. Figure 3.5.2 is a photograph of an operating 13x10.4 cm active area LED display formed with a mosaic of 4x5 four-edge abuttable modules of the type shown in Figure 1.

The size of the standard module was selected to accommodate either a 64x64 pixel, nominal 25 pixel/cm resolution graphics LED array or a 128x128 pixel, nominal 50 pixel/cm resolution video LED array where the binary equivalents $64=2^6$ and $128=2^7$ are compatible with standard silicon digital drive/address circuitry. The choice between different digitally compatible module sizes represented a tradeoff between minimising the total number of modules to display mainframe electrical connections, in large displays, and achieving a module small enough to permit reasonable flexibility in the dimensioning of displays built using the modular building block approach. The ultimate maximum size of a module is limited by the current sourcing and sinking capabilities of the modules silicon integrated circuit drivers.

The primary performance advantage gained from using modular display construction stems from the fact that the image legibility of the complete display is the same independent of the number of modules used to construct it. This follows because the display modules are all updated with information in parallel (ie. at up to their 500 Hertz refresh rate capability) with each module acting effectively as an independent display. As a result, display size does not influence display maximum image speed, image quality, image positioning accuracy, emitted luminance, contrast, or viewing angle, since these quantities are known and fixed when the display module is constructed. An in-depth discussion of both the advantages and disadvantage of modular flat-panel display construction is contained in Reference 3.5.4; see also paragraph 3.5.4.1.

Although designs for LED displays having up to 13 cm x 13 cm active areas with just slightly over a 2.5 cm depth have been formulated for display locations in front of head-up display optics, the large area LED displays demonstrated to date have had an approximately 7 cm depth. This depth would not be expected to increase for larger area displays, where display surface areas of up to about 20 cm square are presently being considered.

3.5.3.5 LED Failure Mode

LEDs have two potential failure modes. Under the forward biased light emitting drive condition, excessive drive current densities can result in junction temperatures rises which permanently alter the diode luminance/current density characteristics, or for extreme overdrive conditions can destroy the device. Junction temperatures above approximately 200°C, whether induced through driving the LED or by elevated ambient temperatures, can cause this type of degradation in green GaP LEDs. In general, increasing arsenic compositions in the $GaAs_xP_{1-x}$ tertiary compounds causes the temperature limit to be reduced. When adequately cooled the GaP LEDs can tolerate continuous current densities of up to about 200 A/cm^2 without damage and higher levels in a pulsed drive mode. Comparing this drive limit with the 1.5 to 3 A/cm^2 maximum current densities needed to satisfy practical aircraft dot-matrix display applications, explains the large tolerance the displays exhibit in the presence of inadvertant short duration overcurrent or timing fault induced 100% duty cycle drive conditions.

The second potential LED failure mode occurs when the reverse bias breakdown voltage limit of the LED is exceeded by a sufficient amount. Depending on the diode fabrication techniques used, either the Zener or the avalanche multiplication mechanisms (that are made use of in silicon Zener diode applications) will be operative.

Both types of potential LED failure mode can be completely avoided through proper design of the LED display. The excellent reliability record of LEDs in practical display applications is testimony to the ease of eliminating these failure modes.

3.5.3.6 Luminance Degradation

Luminance degradation as a function of operating time cannot be avoided. All of the present light emitting display technologies including CRTs, plasma panels, EL panels and LED panels exhibit some degree of luminance degradation as a function of operating time. For LEDs operated near their current density/junction temperature limits, the half life (time to degrade to half the initial luminance value) of the LEDs is about 15,000 hours for GaP liquid phase epitaxial LEDs and is 25,000 hours for GaP vapor phase epitaxial LEDs. Red LEDs typically exhibit somewhat shorter half lives under the same operating conditions.

The half life of LEDs increases significantly with reduced junction operating temperatures and current densities, with the temperature of the diode junction playing the most important role. As an illustration of this, half life tests run on continuously scanned XY matrix arrays of green vapor phase epitaxial LEDs for a period of five years (ie. 43,800 hours) predict luminous half lives of at minimum 500,000 hours. The 25 pixel/cm LED arrays used for these tests were operated without heat sinks and using drive conditions consisting of 500Hz refresh rate current pulses of 100 mA amplitude and 10% duty cycle in a 25^{o}C ambient temperature environment. This drive condition is equivalent to that used for the graphics portrayal LEDs built to date with the exception that the test uses a factor of 20 higher pulse duty cycle in order to stress the array.

3.5.4. ADDRESSING/DRIVING

3.5.4.1 Addressing Techniques

Lacking either inherent memory or a convenient method of either forming or incorporating an active control drive at each LED location, the most effective method available for activating LED displays is through parallel sequential scanning of data onto the display. When displaying segmented characters (such as numeric readouts) the readouts are typically scanned so that all of the data needed to describe each character to be displayed is provided in parallel as each readout location is sequentially scanned. On dot-matrix LED arrays layed out on orthogonal axes, this time sequenced scanning technique is referred to as matrix addressing where data is entered and displayed one line at a time.

When dot-matrix display arrays of greater than 2x2 pixels are to be addressed, a saving in the number of drivers and a reduction in the number of address lines is achieved when matrix rather than direct drive addressing is used. It can moreover be shown that an array of $N=n_x.n_y$ pixels, where n_x is the number of columns and n_y is the number of rows, will require the fewest number of drivers, n_x+n_y, if the number of columns equals the number of rows. This is also considered in Section 2.

3.5.4.2 Constraints on LED Array Size

The total time averaged current, I, required to drive an individual LED at a specified luminance level is the same independent of the addressing/driving technique employed to operate it. This implies that in a dot-matrix array of n_x columns and n_y rows and containing $N=n_x.n_y$ total pixels, drivers employed in a matrix addressing approach would have to have a time averaged row current drive capacity of $NI/n_x=n_yI$. In addition, either the row or the column driver circuits must be capable of handling a peak current pulse amplitude of up to n_x times the average row driver current, that is n_x^2I, or n_y times the average column driver current, n_y^2I. This peak current pulse requirement must be met by the array line scanning drivers and applies to all four possible dot-matrix array driver configurations (ie. common cathode current source, common cathode current sink, common anode current source and common anode current sink). The disadvantage of matrix addressing as compared to direct address is therefore the higher average and pulse current capacity requirements on the driver circuitry. These requirements can act as practical constraints on how large a single LED display panel can be made, as can the electromagnetic interference (EMI) induced by high pulsed currents.

Another potential constraint on the picture element dimensions ($n_x.n_y$) of a single LED display panel is the saturation of the LED luminance. To hold the perceived (ie. time averaged) luminance of a LED display constant while scanning larger and larger array sizes requires that the pulse duty cycle be reduced to accommodate the larger number of rows or columns to be scanned during the established display refresh time period and that simultaneously the LED instantaneous pulse current be increased so as to maintain the same average drive current and hence luminance. Eventually this process results in increasing the LED current density to the point where luminance saturation occurs. Further array size increases can then be gained only with a reduction in the average luminance the display is capable of producing. This limitation, or variations of it based on voltage saturation, power saturation or simple response time limitations, is shared in varying degrees by all dot-matrix display technologies.

3.5.4.3 Rationale for Modular Display Surfaces

The actual magnitude of the current density induced luminance saturation limit varies with the LED materials used, the techniques used to fabricate the LED junctions and the metalization structure/metallurgy employed. Red emitting LEDs in general have lower pulsed current density saturation limits than do green GaP LEDs, however neither would be adequate for use in fabricating single panel 875 or 1024 line high luminance video displays, for instance. To avoid the ultimate size limitation on sequentially scanned matrix addressed displays, the objective of LED display development has been the development of mosaic displays that use independently refreshed display modules to limit to a small manageable quantity the number of pixels that have to be sequentially addressed using the line-at-a-time address technique. Using this approach, drive current and saturation problems have been successfully avoided for pulse duty cycles of as low as 0.5% or 200 sequentially addressed LEDs per module. It should be noted that in general driver circuit capacity problems are encountered before saturation limits are reached.

3.5.4.4 LED Drivers

The low voltage drive requirements of LEDs can usually be satisfied using commercially available silicon transistors and/or integrated circuits selected to meet the necessary military specification. The choice between common anode and common cathode drive circuit configurations is usually based on the electrical lead current handling capacity of the LED array design employed, which in turn is based on minimising LED junction obscurations due to wires or surface metalisation layers. The common terminal driver, whether it is associated with the common cathode or the common anode configuration, is the one which is scanned and which must handle the high instantaneous current loads. Its primary function is that a switch having a virtually constant saturation voltage independent of whether it is passing the current of one or all of the LEDs in a data addressed row or column.

Whether the inputs to the data line drivers are provided by serial shift registers or by parallel multiplex circuits, the LED address circuitry used with the driver generally must be able to store/latch the transient input data until new data is entered. The essential feature of the data driver is that it functions as a current control circuit. Enabling this circuit using a pulse duration control signal fed simulatenously to all data drivers has provided one straightforward method of controlling the overall luminance of the display under either automatic or manual operator control without influencing the relative luminances of the data displayed. Circuit designs for use with LED displays are still evolving, particularly for video drivers where digital grey shade storage and control are necessary.

For applications such as the graphic display module shown in Figure 3.5.1, it was found necessary to have custom made silicon integrated circuits built in order to make the combined row and column address/driver circuits small enough for mounting on the sides of the module. The advantage of this construction approach is the reduction in driver line power losses, due to the shorter lead lengths, and the reduction in external module connections (ie. reduced from 128 to 16 parallel data lines/module plus power, ground, clock, control and status sensing for the graphics display module).

3.5.5. SYSTEM INTERFACE

The low signal level requirements present at the input to LED display address lines make these displays compatible with virtually all available types of logic, multiplex and memory interface circuitry. The type and complexity of the LED display system interface is therefore determined almost exclusively by the intended display application and in particular by the complexity and rate of change desired in the information to be displayed, not the display technology to be employed.

3.5.6. VISUAL CHARACTERISTICS

3.5.6.1 Optical Properties

The legibility and efficiency achievable with a LED display depends rather critically on the effectiveness of the optical design which is implemented. In general the design of a LED display should treat the LED material, the substrate to which it is affixed, visible electrical connections to it, any optical coatings applied to the display surfaces and the optical filter or cover glass employed as integral parts of a single composite optical system design. Typical LED processing results in LED wafers and dice having flat smooth specularly reflecting surfaces of between 30 and 38% spectral reflectance prior to encapsulation and 18 to 23% afterwards. The diffuse reflectance associated with the LEDs varies from much less than 1% for vapor phase epitaxial devices up to 2% for some liquid phase epitaxial devices.

The objective of optical filtering any type of head down display is to reduce the maximum combined display reflectance to less than approximately 0.5% or a reflected background luminance of approximately 171 cd m^{-2}. The concept behind this guideline is that head-down displays having sufficient emitted luminance to be legible against the 171 cd m^{-2} background luminance should also be adequate in the glare induced veiling luminance environment created when the sun is within the pilot's instantaneous field of view.

A variety of optical designs capable of satisfying the foregoing requirements have been developed for LEDs. The most cost effective of these designs utilise colour transmission selective filters. Since the inherent diffuse reflectance of the LED is low, the primary objective of the filters is to maximise the filter transmittance to the LED light while significantly reducing specular reflectance and making a slight reduction in the diffuse component. A filter developed for use with green GaP LEDs, and which meets military specification environmental requirements, may be used as an example of a filter requiring little in the way of special display surface treatment. The filter utilises a laminated sandwich structure consisting of an antireflection coated UV attenuating filter, a neutral density circular polarizer, and an IR absorbing filter with an EMI attenuating antireflection coated rear surface. The circular polarizer effectively attenuates the LED specular reflectance component, the colour and neutral density filtering attentuate the diffuse component and the antireflection coatings minimise the external filter surface Fresnel reflections. A combined reflectance of 0.30% has been achieved using this filtering method. Such techniques are expected to permit the display of up to 8 shades of 'grey'. While the foregoing approach accomplishes the filtering objective, it also restricts the display emitted luminance to between 27 and 35% of that emitted by the LED. As a result more efficient filtering techniques have been developed which concentrate on improving the display surface optical design. One method is essentially equivalent to the black matrix shadow mask approach used on colour CRTs. The most promising approach, based on experimental results obtained to date, involves the application of refractive index matching antireflection coatings to the LED arrays. Combined reflectances of well below 0.5% are expected, while eliminating the need for the circular polariser which at best transmits only about 41% of the LED emitted light.

3.5.6.2 Luminance/Contrast

The present performance of green 25 pixel/cm GaP LED arrays operated at a 1 mA/LED time averaged drive current (ie. 64 mA, 31.25 μs duration pulses every 2 ms) is 7.54 x 10^3 cd m^{-2} (2,200fL) of luminance spatially averaged over a 200 μm diameter LED measurement area (ie. 15.4 x 10^3 cd m^{-2} for laboratory devices). When this luminance is area averaged over the surface of a dot-matrix display character, symbol, or image so as to include both emitting and non-emitting areas (ie. assuming no emission between LEDs) an area averaged luminance of 1.5 x 10^3 cd m^{-2} (440fL) is obtained. Roughly equivalent performance can be achieved with red LEDs, which, while more efficient radiometrically, lose this advantage due to the characteristics of the eye.

Contrast ratios achievable using head-down LED displays vary depending on the filtering techniques employed. A low altitude (green LED numeric readout) radar altimeter in the F-111/FB-111 and EF-111 series aircraft produces an area averaged emitted to reflected luminance contrast ratio of one (or an emitted plus reflected divided by reflected luminance contrast of two) in a 100 x 10^3 Lux (10,000 fc) illuminance environment. A green 7.8x2.6 cm active area 25 pixel/cm resolution LED alphanumeric readout dot-matrix display being produced for evaluation for a potential F-16 data entry display application has been characterised as having an area averaged emitted to reflected luminance contrast ratio of between two and three.

The LED antireflection/refractive index matching filter techniques are planned for use with video, multi-colour and advanced versions of numeric, alphanumeric and graphic displays; this technique should permit eight grey shade legibility on LED video displays.

Radiant intensity spectra of a red LED standby sight plotted as a function of heat-sink temperature are shown in Figure 3.5.5. The intensities are measured in radiometric units and show that as the temperature increases, the peak intensity decreases and moves to longer wavelengths. The effect on perceived brightness is even more pronounced since the eye's sensitivity drops rapidly with wavelength in this region from 72.8 lm W^{-1} at 650 nm to 11.6 lm W^{-1} at 680 nm.

3.5.6.3 Image Quality

Like other dot-matrix display techniques, the LED display exhibits excellent image edge definition. Special design eliminates visible indications of electrical crosstalk. Optical crosstalk between "on" and "off" elements is most severe in monolithic flip chip GaP LED arrays where the material is nearly transparent to the light it generates and no physical boundaries exist between adjacent LEDs. Even in this type of array the luminance measured at an "off" LED immediately adjacent to an "on" LED is typically less than 2.5% of the "on" LED luminance. A greater than 5% optical crosstalk level is capable of producing a visually noticeable effect for a display adjusted to provide a peak image contrast ratio of ten to one. Increasing the contrast by either increasing luminance or reducing the ambient will of course eventually make the crosstalk noticeable.

Dot-matrix displays of all types exhibit spatial variations in pixel luminance and potentially also in pixel colour. These variations can stem both from variations in the drivers used to apply signals to the pixels and from the differences in the electro-optical characteristics of the individual pixels. LED displays having normalised standard deviations in luminance of 12% of the mean value or less have been found to provide satisfactory graphics display image luminance uniformity provided that the luminance variations are spatially randomised across the display surface. By comparison, variations perceptable as row or column luminance variations can, at the same variation magnitude, be obtrusive due to the larger size of the line image.

Luminance variations permissible on displays intended for aircraft video applications are determined by the need to avoid overlap between adjacent grey shades rather than just the issue of whether the variations are noticeable. Using the overlap criteria, a maximum variation of up to 17.2% from the mean grey shade operating level would be permissible for an eight grey shade, $\sqrt{2}$ grey scale ratio video display. Luminance uniformity distributions having a normalised standard deviation of between 8 and 10% from the mean would therefore be capable of satisfying this video LED display luminance uniformity criterion, which can be achieved using developed 50 pixel/cm monolithic chips. However, further processing improvements are desirable to achieve higher chip yields. In general LED arrays fabricated at any resolution using vapor phase epitaxial techniques result in lower luminance variations than when liquid phase epitaxy is used.

Colour uniformity variations either due to process control constraints or temperature variation have proved insignificant for green or red LED's.

3.5.6.4 Flicker/Dynamic Visual Effects

Current production, prototype and developmental aircraft cockpit LED displays employ 500 Hz or higher refresh rate in order to avoid both static and dynamic display image flicker effects. Flicker associated with display imagery which is static or nearly static on an observer's retina may be overcome at a refresh rate of between 50 and 60 Hz, the higher rates being required for larger LED displays. Dynamic flicker or more accurately the appearance of multiple spatially separated images occurs at these low refresh rates as a result of motion of the display image on the retina of the observer's eye. The effect is observed under vibration and also when the observer averts his eyes to look at display information located elsewhere within the cockpit. This dynamic image phenomenon is experienced for all periodically refreshed display media having image persistence durations less than the refresh period (ie. P-43 phosphor CRTs, plasma panels, TFEL and LED are examples). The effect is emphasised in dot-matrix displays due to the sharpness of the imagery portrayed. Refresh rates of 450 Hertz and greater effectively eliminate the phenomenon under practical aircraft cockpit illumination conditions (3.5.6).

3.5.6.5 High Resolution Graphics/Video

LED arrays with resolutions of up to 50 pixels/cm have been successfully demonstrated in both green and red monolithic chips (green in sizes of up to 2.6x2.6 cm). Military specification qualified devices being applied as film annotation arrays in airborne reconnaissance cameras utilise resolutions of up to 46 pixels/cm. A number of arrays at resolution between 40 and 50 pixels/cm have been applied to HUD and HMD displays and to date have been found to provide satisfactory performance when displaying alphanumerics and graphic symbology.

Head-down displays suitable for eight grey shade (ie. $\sqrt{2}$ grey scale ratio) video information portrayal are under development. A grey scale capability was demonstrated by the Japanese in a low resolution display in 1969; recently it has also been demonstrated on a 50 pixel/cm high resolution display surface. See also Section 3.5.7.7.

The very high resolutions being sought for use in HMD video image sources (ie. 200 pixels/cm or greater) have not been attempted using LEDs. Diode junction formation at these resolutions would be feasible; however, a significant advancement in present LED electrical connection fabrication processing techniques would be required to achieve reliable devices. Purer LED substrates would probably also be required to avoid problems in achieving adequate luminance uniformity. No research to develop very high resolution displays has been reported.

3.5.6.6 Colour

Very little colour LED research has been conducted. Red, orange, yellow and green single colour LEDs, due to their importance in consumer and commercial products, have received the greatest research and development emphasis. However, this has been restricted largely to improvements in existing products. Blue and dark green emission colours, which have been demonstrated in large energy gap materials such as gallium nitride and silicon carbide, have been virtually ignored from a research and development standpoint. Difficult processing, very low initial emission efficiencies, and a generally conceded low prospect for high volume device sales in green and blue displays has been responsible for this situation. Metal-insulator-semiconductor LEDs have fared little better, an exception being the dark green emission zinc telluride devices.

Lacking an efficient material capable of producing blue, and therefore potentially also green and red, a full colour LED display is at best a possibility for the distant future. Gallium phoshide which has served as the basis for efficient green, yellow, orange and red single colour LEDs has been the subject of very modest government funded multi-colour LED display research (3.5.7). Two terminal multi-colour hybrid and monolithic LEDs utilising current density to control the mixing of the red and green primary emission colours and using pulse duration to control luminance have been demonstrated. Attempts to achieve spatially uniform mixed colour that would be satisfactory for application to large area multi-colour displays proved to be beyond the means of the modest development efforts conducted.

More recent multi-colour display research has concentrated on monolithic LED arrays utilising independent red and green primary colour diode junctions (to provide yellow and oranged mixed colours) in a superimposed geometric structure. This structure is suitable for low resolution displays because the colour mixing occurs within the LED. The technique has also provided LED efficiencies approximately the same as those of single colour red and greens LEDs. Colour dot resolutions of 16, 25 and 50 colour dots/cm have been demonstrated, the latter is up to 12.6 cm square monolithic chips. Improvements in colour uniformity and demonstration in the four-edge abuttable 2.6 cm square modular building block format, needed for large area head down displays, still must be accomplished to prove the feasibility of this multi-colour display approach.

3.5.6.7 Viewing Angle

The viewing angle associated with LED displays depends on the optics used to form the final display product. The use of restricted viewing angle lensed LED indicators and displays is common in consumer product applications where it is assumed that legibility will be achieved by orienting the display. In head-down aircraft display applications the displays are attached to instrument panels at locations which can result in viewing angles of up to about 45^0. The latter application is satisfied using flat LED arrays. These arrays may be viewed at angles approaching 90^0 from a normal to the display surface. This is possible because the luminance of the characters depicted using these LED arrays remains approximately constant as a function of viewing angle, although the apparent foreshortening of display characters experienced at large viewing angles (ie. $>60^0$) should be avoided.

3.5.7. STATE OF DEVELOPMENT

3.5.7.1 Head-Up Displays (HUD)

It has become conventional to construct head-up displays with standby sights, optically mixed into the collimation system, which may be used if the cathode ray tube or its drive circuits fail. It is advantageous for the purpose of optical combination for the standby reticle to be of a different colour to the green cathode ray tube and they have conventionally been implemented in red. Since red LED's are particularly efficient and crisp definition is required, a fixed-format light emitting diode device is very suitable and has been successfully evaluated in flight. A device for a typical standby sight is shown in Figure 3.5.3, before the processed slice has been cut into individual devices, and consists of a central 'pipper' diode 0.17 mm in diameter surrounded by a separately addressable segmented circle 1.7 mm in diameter. It can be seen that the aluminium metalisation has been defined as grids over the diode areas to spread the current and give uniform luminscence.

The luminance of the two types of diode as a function of current density at 20^0C is shown in Figure 3.5.4. The required maximum luminance for standby sights is approximately 30×10^3 cd m^{-2}, which can be achieved with current densities below 1 A mm^{-2}. In fact brightnesses much in excess of this figure are achieveable with the 'pipper' diode, since its small area involves currents of less than 50 mA. The same is not true for the outer-circle diodes. With an area of just below 1 mm^2 currents of the order of 1 A are required to achieve the specified luminance. Even with massive heatsinking, the thermal impedance of the GaAs results in a significant junction temperature rise which causes the luminance to saturate, as shown in Figure 3.5.4.

Life-test results of the outer diode areas, driven at current density of 0.80 A mm^{-2}, corresponding to an initial 20^0C brightness in excess of 35×10^3 cd m^{-2}, are summarised in Figure 3.5.6. Even at 125^0C times to half brightness in excess of 10^4 hours are obtained.

These results demonstrate that LED devices are ideally suited to standby-sight applications, provided that the format is designed to minimise individual junction areas. The total size possible for a single monolithic device is determined by the size and shape of the starting epitaxial wafer and by the internal diameter of the diffusion capsule. The largest standby sight produced to date measures 20x15 mm and contains 36 separately addressable areas.

3.5.7.2 Helmet-Mounted Displays (HMD)

Whereas helmet mounted sights have found applications in target designation and weapon aiming it is highly desirable to make provision for information display which include target information, threat warning, weapon status and/or provision for cueing a pilot onto a target detected by another sensor (eg. a radar). In such a display, the optical solution adopted is shown schematically in Figure 3.5.7. Light from the display is collimated at the eye by curved surfaces on the exit face of the prism and at the combiner on the helmet visor. Since the wavelength of the light is close to the limit of the eye's sensitivity, a dichroic coating can be used which has a high reflectivity for the LED without producing noticeable colouration of the outside scene.

A monolithic common-cathode display intended as a threat-warning indicator in helmet-mounted systems is shown in Figure 3.5.8. This display, measuring 5x5 mm, contains 65 individually addressable diodes. Many other formats of the same complexity are possible. The limiting factors in the design of such devices is the need to bring the conductor tracks to the outside of the chip and the comparatively large size of the bonding pads.

Such monolithic arrays have restricted formats, chosen at the design stage, which can be used for dedicated tasks only, such as sighting or threat warning. Matrix addressable displays, on the other hand, would be capable of performing a variety of functions and thus give greater flexibility to the design of avionic systems. The matrix displays need to have a resolution of at least 4 lines mm^{-1} and to be capable of achieving a mean brightness of approximately 15×10^3 cd m^{-2}.

A fabrication technique which uses standard commercial material is illustrated schematically in Figure 3.5.9. The $GaAs_{0.6}P_{0.4}$ slice is processed as for the common-cathode displays with a diode matrix being produced. Each p-type area has an individual contact pad delineated on it and the entire n-type back surface has a single ohmic contact applied over it. After cutting it to size the device is bonded to a metallised ceramic substrate, and air isolating channels are formed between the diode columns. These channels penetrate the ceramic substrate through the metallised layer to align the device automatically for subsequent packaging. The rows in the matrix are then formed by conventional stitch bonding techniques to join up appropriate p-contact pads.

This technique has proved satisfactory for producing small arrays for helmets, and a packaged 32x32 array, with 4 lines mm^{-1} resolution has been supplied in quantity.

In the absence of suitable integrated drivers the array is driven by discrete transistor stages The array and bond wires are protected from damage by an anti-reflection-coated corundum (a-Al_2O_3) window.

Future developments include both improving the efficiency of the LEDs by optimising the material preparation, and increasing the resolution to the level at which HMDs may become a primary display surface for avionic systems. Another important development is that of integrated logic/drivers capable of handling the peak currents required. This will enable the display and electronics to be mounted on the same package to increase reliability, and more importantly lead to a decrease in weight on the pilot's helmet.

A helmet-mounted display with a matrix-addressed reticle (20x23 addressable points) was first evaluated by the Naval Air Test Centre, for energy management and aircraft limit indication to a combat pilot. A series of trials (Ref.3.5.8) has provided full validation of the concepts explored. A brief trial was also carried out under the sponsorship of the UK Ministry of Defence of the use of a similar display in helicopters for head up indication of principle navigation parameters and has been favourably reported on. Assessments by British Aerospace and the Royal Aircraft Establishment of matrix-addressed helmet displays in fixed simulators, in moving base simulators reproducing flight vibration, and in actual flight, continue as this report is being compiled. A version suitable for flight and completely integrated with the UK Mk IV helmet has been developed, undergone blast tests appropriate to ejection and is under evaluation.

3.5.7.3 Head-Down Numeric Displays

A photograph of an operating low altitude radar altimeter developed and produced for use in all F-111/FB-111/EF-111 series aircraft is shown in Figure 3.5.10. The instrument is believed to represent the first installation of an instrument incorporating a LED display in an operational military bubble canopy type aircraft. The altimeter uses four 7.1 mm high green LED readouts to provide the pilot with precise altitude information. The digitally driven round-dial indicator provides altitude trend information and a red LED provides a low-altitude warning indication. The unit also includes an illuminance sensor, located adjacent to the numeric readout and warning indicator displays, which is used to automatically control the luminance of these displays over their entire operating range. A manual brightness control allows the pilot to adjust the LED displays to a comfortable level for night viewing.

During flight tests by Strategic Air Command and Tactical Air Command aircrews, the pilots rated the legibility of the LED readouts as being very good and the instrument overall as a significant improvement over existing conventional indicators. The overall reliability of the instrument for any single component failure was specified at 10,000 hours mean time before failure and the instrument was provided to the USAF with a 5000 operational hour (as indicated by a rear panel elapsed time indicator) repair or replacement warranty.

A variety of different LED numeric displays applied to applications such as clocks, status readouts, etc, are currently in use in the less severe illumination environments found in commercial and private aircraft. Similar applications of LED numeric displays within conventional electromechanical instruments have been developed by Smiths Industries and Plessey for use in military aircraft such as the British Aerospace Hawk.

3.5.7.4 Head-Down Programmable Pushbutton Switch/Keyboards

An operating programmable pushbutton utilises a 35x16 pixel array of green gallium phosphide high efficiency LEDs at a resolution of 16 pixels/cm and has an active area of 2.2x1 cm. The array is designed to permit the display of two rows of up to six character font or a lesser number of vertically centered larger font characters. The switches contain their own individual drive and address electronics and can be used either individually or can be four edge abutted to form a multi-function programmable keyboard of any desired size.

The information portrayal capabilities and methods of interfacing and utilising the switch/keyboard with aircraft systems are being established by Boeing based on the extensive research they have conducted in recent years aimed at developing and refining effective multi-legend interactive display techniques and information portrayal methodologies. The switches, which are being developed to meet full military environmental test conditions, will be available in mid 1983.

An alternative LED programmable pushbutton demonstrator which utilises a single display panel containing both a scratch pad display and a 3x3 matrix of switch displays overlayed by a clear plastic touch panel has been developed. Each switch area in this display contains two separated rows of four character word, 5x7 dot-matrix font red LEDs. In a newer version currently under construction the switch matrix size is increased, the switch word lengths have been extended to eight characters per word and higher luminance yellow LEDs are used. Both displays have a 20 pixel/cm resolution but neither has as yet been designed to be legible in a bubble canopy aircraft cockpit environment.

3.5.7.5 Head-Down Data Entry Display

The data entry display shown operating in the photograph of Figure 3.5.11 was developed for use as a feasibility demonstrator/simulator test display. The display has a 7.8x2.6 cm active area viewing surface and was constructed by edge abutting three 2.6 cm square nominal 25 pixel/cm resolution green LED graphic display modules (see Figure 3.5.1). The display provides an area averaged contrast ratio (ie. emitted luminance divided by reflected luminance) of in excess of two.

3.5.7.6 Head-Down Vector Graphics Displays

Two advanced development model versions of a 25 pixel/cm resolution green LED graphics display are currently nearing completion. The photograph of the first display was shown in Figure 3.5.2 and its visual characteristics have been previously described. This 320x256 pixel (13x10.4 cm) display system was designed for use in an extensive flight simulator evaluation test program to be conducted by the U.S. Air Force Flight Dynamics Laboratory. The purpose of the testing is to assess pilot performance/acceptance of the 25 pixel/cm dot-matrix graphic information presentation technique and to establish display information format restrictions, if any, that would be necessary when applying the display to airborne flight control and avionic data monitoring piloting tasks. The display system is designed to accept avionic input data rates of up to 50 Hertz and, through display system data processing, provide interpolated/extrapolated imagery at selected frame rates of up to 250 Hertz (ie. a constant 500 Hertz refresh rate is used). The display is programmed to portray formats utilising from low to medium speed imagery for the purpose of initial testing (ie. an electronic attitude director indicator (EADI), an electronic horizontal situation display (EHSI), a navigation-vectoring display (NI), a precision approach indicator display (PAI) and an engine status indicator (EAI) in two formats). Later phases of the program are to assess advanced display formats and high display surface image speed information portrayals.

The second graphics display is a flightworthy version which has a 13 cm square nominal 25 pixel/cm resolution display surface made up of 25 of the previously described green LED modules.

3.5.7.7 Head-Down Video Displays

Nearing completion is a nominally 50 pixel/cm 2.6 cm square, grey shade (ie. 2 grey scale ratio) video demonstrator display that is being developed under the joint sponsorship of the Canadian Department of Industry, Trade and Commerce and the U.S. Air Force Flight Dynamics Laboratory. A photograph illustrating the grey shade rendition capability of a preliminary green LED array, developed to assess both the breadboard drive/address electronics and the 128x128 element solid state image plane video camera to be used with the final deliverable LED array, is shown in Figure 3.5.12. The demonstrator display was restricted to the size of a single four-edge abuttable module (128x128 pixels at about 50 pixels/cm resolution) to conserve resources. Since the electro-optical performance demonstrated by a single module gives a direct measure of the performance to be expected from fully populated 525, 625, 875 or 1023 line video displays, formed as a mosaic of modules, the restricted area demonstration is still quite meaningful. Array alignment, grey scale rendition, luminance uniformity, colour uniformity, luminance control, optical and electrical coupling, and module edge abuttment potential were the primary development criteria for this display. Luminance output and display reflectance were secondary development issues; however, measurements on sample arrays under the video drive conditions have yielded 1.4 x 10^3 cd m^{-2} outputs. The sample arrays did not incorporate the refractive index matching film techniques previously described.

Results obtained to date indicate that single colour video LED displays suitable for use in bubble canopy aircraft cockpits are feasible. The feasibility of video multi-colour displays utilising the demonstrated 50 dots per cm colour LED arrays cannot yet be assessed since necessary research into monolithic chip electrical interconnection techniques compatible with four-edge abuttable colour module construction has not been conducted.

3.5.8 Acknowledgements

The authors wish to acknowledge the contributions of Dr D. Wickenden of the General Electric Company p.l.c. (UK), Mr D. Kennedy of Optotek Canada. Part of the UK aspect of this work has been carried out with the support of the United Kingdom Ministry of Defence and part of the United States aspect with the support of the Flight Dynamics Laboratory, US Air Force.

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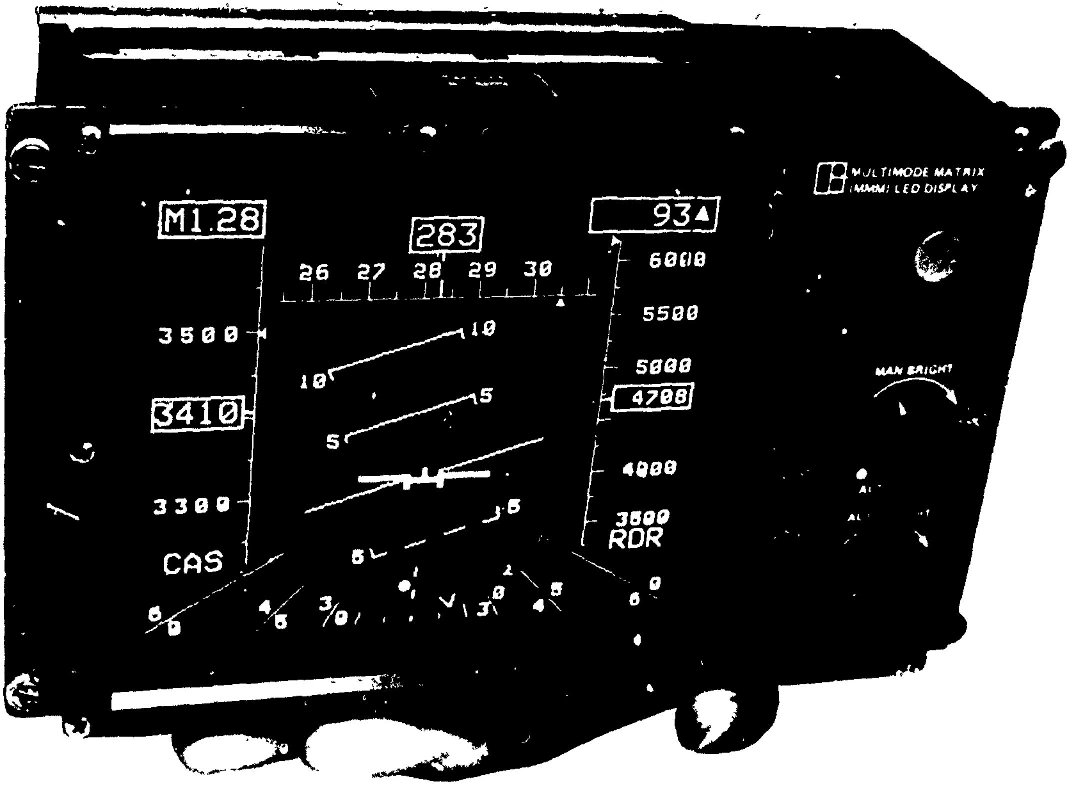

Fig.3.5.1 Green emitting 64 x 64 pixel 2.6 cm square 4-edge abuttable led display module

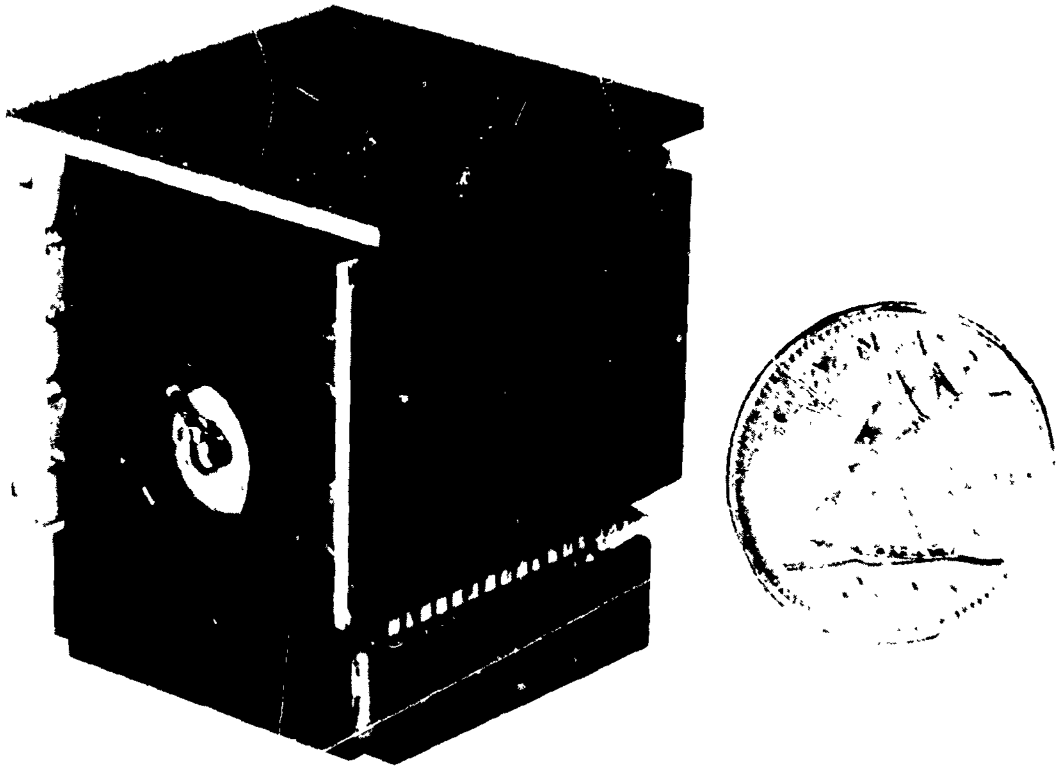

Fig.3.5.2 Photograph of an operating high speed graphics display with a 20 module mosaic surface

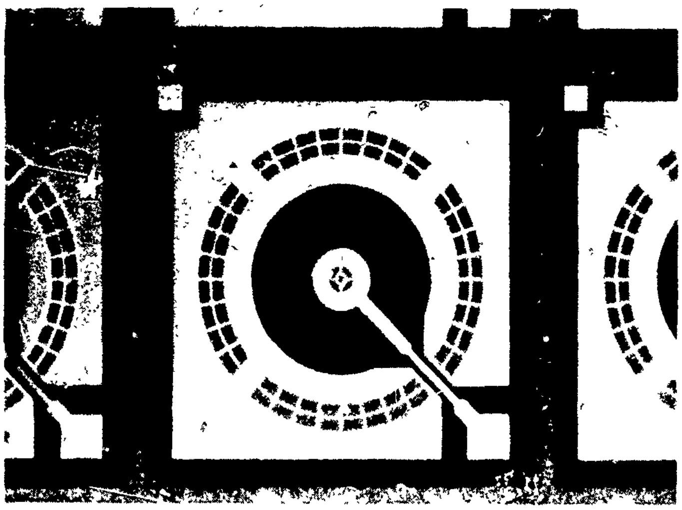

Fig.3.5.3 A typical head-up display standby-sight

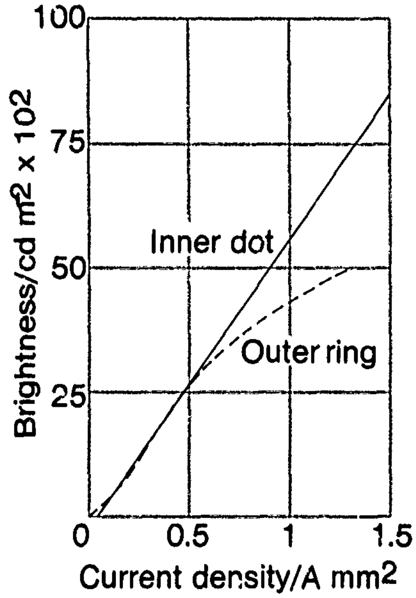

Fig.3.5.4 Brightness of red emitting standby-sight leds as a function of current density

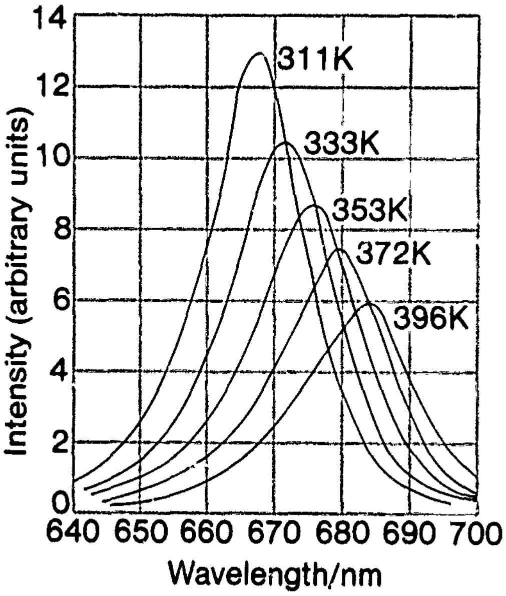

Fig.3.5.5 Radiant intensity spectrum of red emitting leds as a function of heat sink temperature

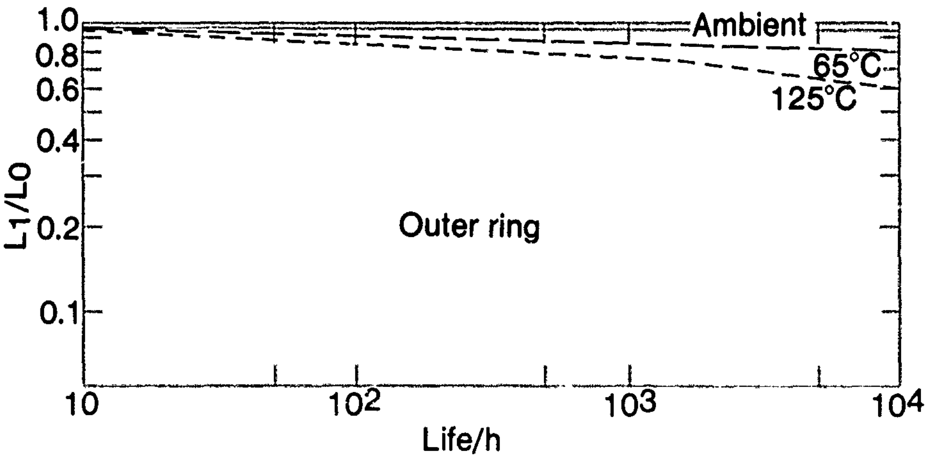

Fig.3.5.6 Standby-sight life test results: i-0.66a, j=0.815 amm-2

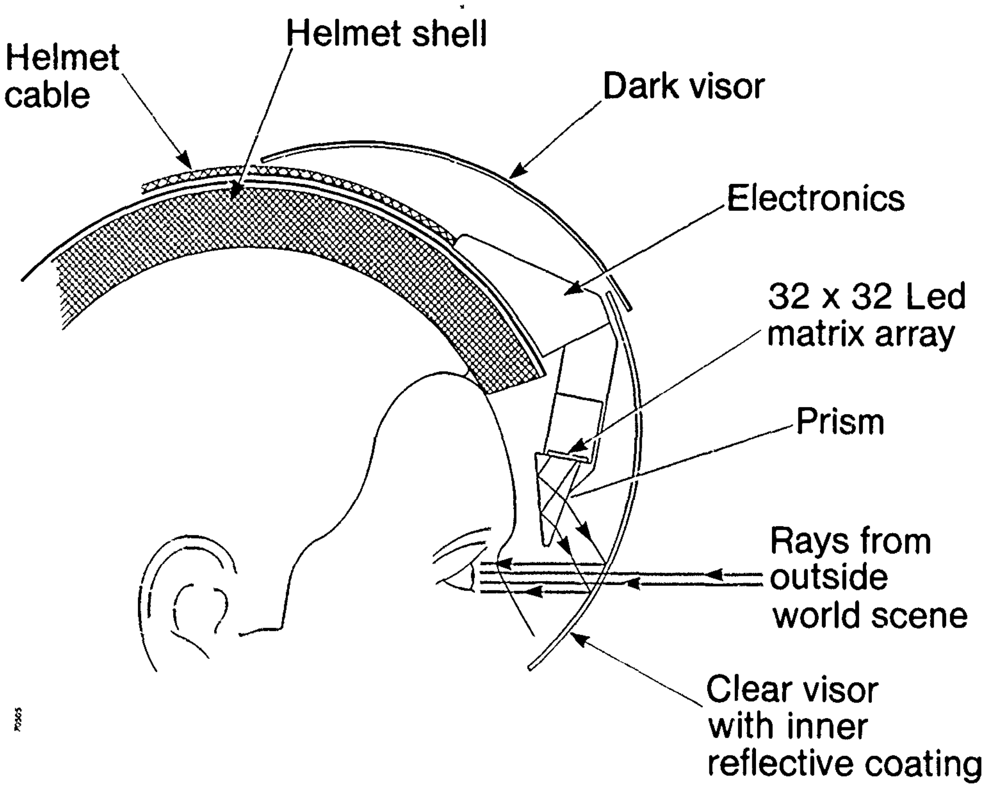

Fig.3.5.7 Cross section of the helmet mounted display

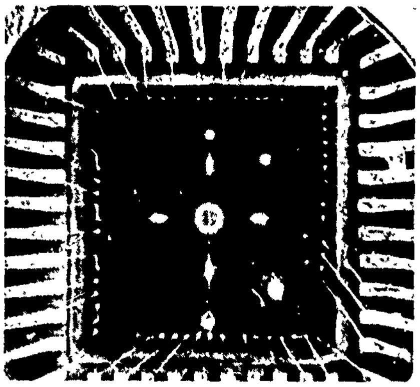

Fig.3.5.8 Helmet mounted threat-warning indicator

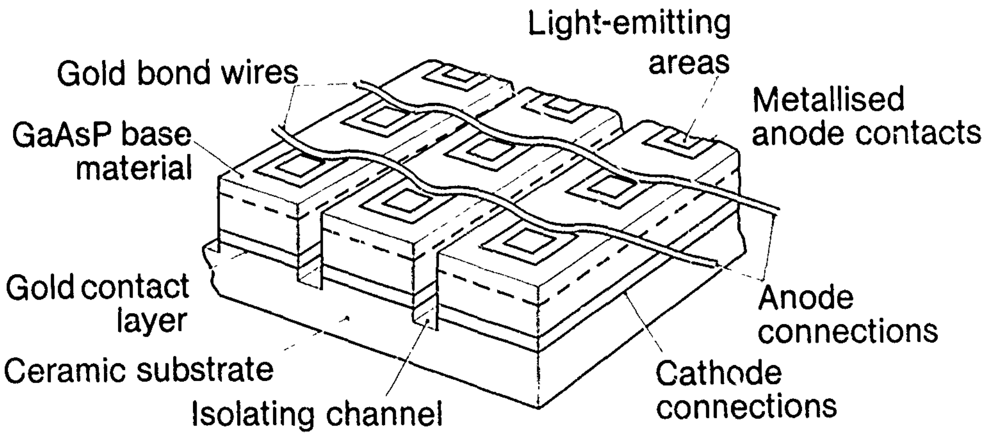

Fig.3.5.9 Method of fabrication of a monolithic led matrix

Fig.3.5.10 Photograph of an operating f-111 green led numeric readout low altitude radar altimeter

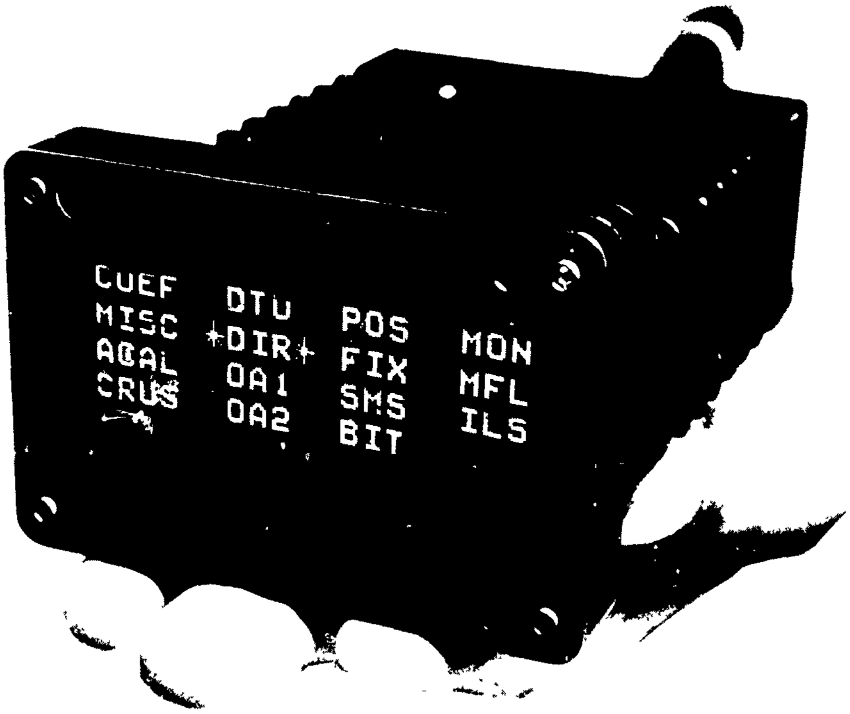

Fig.3.5.11 Photograph of an operating green led data entry display with a three module mosaic surface

Fig.3.5.12 Photographs of an operating 2.6 cm square 128 x 128 pixel breadboard video display surface (full scale)

3.6 ELECTROLUMINESCENT DISPLAYS

3.6.1 HISTORICAL SURVEY

Electroluminescence (EL) is defined as the light generated by a phosphor under the influence of an electric field. Depending upon the phosphor material and electrode geometry, light may be generated by an alternating (ac) or continuously applied (dc) field. For each type, the devices may be fabricated with powder EL or thin-film EL materials.

One cause of light emission is related to the energy released upon recombination of minority and majority carriers in a solid at recombination centers. Alternately, the emission is due to impact excitation of luminescent centers by charge carriers which have been accelerated by high electric fields within the solid. The first process is that of light emitting diodes and is called injection-luminescence (see Section 3.5). The second, which does not require a perfect crystal and works well for either ac or dc, is called electroluminescence. The variety of EL devices (ac or dc, powder or film) arises from different means of achieving the high field and protecting the device when avalanching occurs.

Significant advancements in the state of the art of EL displays have been achieved during the past decade. Although powders have much improved and are used in certain aircraft applications, the main breakthrough has been in thin-film phosphors. Being highly transparent allows for the use of an absorbing black rear layer for contrast enhancement. Highly non-linear in its luminance versus applied voltage relationship, the thin-film EL allows for direct matrix addressing. Because the ac thin-film EL (TFEL) devices currently represents the greatest investment in time and money and to many, having the most potential, sections 3.6.2 through 3.6.6 will focus principally on ac TFEL. The powders and dc thin-films will be discussed in Section 3.6.7.

The electroluminescence (EL) phenomenon was first discovered by Destriau in 1936, in zinc sulfide (ZnS) with copper (Cu) used as an activator (3.6.1). This discovery led to several efforts to apply the EL phenomenon to lighting. During the 1950's and 1960's, extensive research was carried out to fabricate EL displays using phosphors made by heating (fusing) ZnS:Cu powders. The powdered EL, however, could not be made daylight readable, nor could the brightness levels achieved be maintained for even moderate lifetimes. The limited life resulted from the migration of the activator (Cu) under the influence of the applied electric field. Further, the mechanism of destruction was fast, even at moderately high temperatures. Transparent thin-film phosphors had been made as early as 1934 by DeBoer and Dippel (3.6.2), and later good quality films were made by

Williams in 1947 (3.6.3), and Feldman and O'Hara in 1954 (3.6.4), though not for EL display applications. The earliest thin-film EL phosphors were devised by Thornton (3.6.5) in the late 50's, while the matrix addressing concept for EL panels was patented in 1955 by Piper (3.6.6).

Of the various thin-film devices being developed for display application, the most advanced in terms of practical characteristics is certainly the three layer, double insulated, ac coupled, ZnS:Mn thin-film device first developed by Soxman (3.6.7) (see Fig. 3.6.1). In this configuration, which is now the standard construction, the active light-emitting layer is sandwiched between two transparent high-dielectric-strength layers, and interposed between thin-film electrodes, at least one of which is a transparent electrode on a transparent glass substrate. When viewed from the front, the substrate is transparent through to the rear electrode. The front and rear electrodes are perpendicular to each other to form a crossed matrix pattern.

In the late 60's, Soxman reported on reproducible ac thin-film matrix EL devices having over 50 cd m^{-2} and several thousand hours of life (3.6.7). However, because the rear electrodes were reflective, the contrast ratio was poor. It was suggested that if the rear electrodes could be made transparent and backed with a diffuse black material, or if the second dielectric layer were to be made highly absorbing, the unexcited device could appear quite black, thus providing good contrast in high ambient illumination (3.6.8) (Fig. 3.6.2). The advantages of the black layer were explored by several other researchers during the mid 60's using powders and thin-films (3.6.9-3.6.11). The first thin-film EL display with a black layer was produced in the 1960's by Soxman and Steel (3.6.7 & 3.6.11) who reported on some samples having in excess of 160 cd m^{-2} luminance with flac maintenance (see 3.6.3.2). Major advances were reported at the 1980 SID International Symposium in San Diego. Inoguchi et al (3.6.12) presented data on a three layer thin-film ZnS:Mn EL display exceeding 10,000 hours of life at 340 cd m^{-2} luminance with flat maintenance. Mito et al (3.6.13) presented a second paper describing the reproduction of TV imagery on a 108 x 81 line TFEL panel. However, these displays did not include a black layer. Because they used reflective aluminum rear electrodes with a front-mounted circular polarizer for contrast enhancement,the performance was marginal. The performance of thin-film EL devices using ZnS:Mn, as demonstrated by Soxman, and Inoguchi et al, has since been confirmed by others (3.6.14 & 15).

3.6.2 PRINCIPLES OF OPERATION

The thin-film electroluminescent display is, as described above, made up of a sandwich-structure of conductors and dielectrics with a luminescent phosphor in the center. The thin-films are deposited on a glass substrate, usually starting with an Indium Tin Oxide transparent conductor followed by a dielectric of high electrical breakdown strength, followed by the manganese-doped zinc sulfide phosphor, the second dielectric, and finally, the rear conductor. As stated earlier, a black thin-film layer may be incorporated to the rear of the zinc sulfide phosphor before the rear dielectric or may be used as the rear dielectric. The basic principles of operation are as follows: While the mechanism is not well understood, it is generally agreed that when a high electric field (up to 1-2 x 10^5V cm^{-1}) is applied to the sandwich structure, the ZnS layer, also a dielectric, breaks down into avalanche conduction, and current flows through it to the encapsulating dielectric interface. As the charge builds up on the dielectrics, the internal field in the ZnS is reduced, and conduction ceases until the field is reversed. Thus, one has a pulsed avalanche conduction of the ZnS for each field reversal. The breakdown in the ZnS is apparently initiated by electron tunneling out of the interface sites into the conduction states of the ZnS. At the very high fields involved, the electrons excite the manganese atoms, and photons are emitted, i.e., luminesce, with a characteristic yellow-orange (585 nm) emission. To prevent destructive breakdown under normal operation, the encapsulating dielectrics should not conduct until the field reaches levels of 10-14 x 10^5V cm^{-1}. Should breakdown occur in the encapsulating dielectric layers, a destructive runaway current could flow through the entire structure, causing partial burnout of the active layer. Moreover, since the stored energy is larger, catastrophic failure can also occur (See section 3.6.3.3).

For some time, the phenomenon was considered to be due to ionization. Vlasenko and Yaremko (3.6.16) investigated ac electroluminescence of ZnS:Mn films as a function of thickness between 0.04 and 2μ. Below 0.1μ, the emission dropped very rapidly. Thus, they concluded that the excitation mechanism was impact ionization by accelerated electrons in the conduction band. Now, there is general agreement (3.6.17) that light emission from ZnS thin-films <u>is</u> due to electron impact excitation of the Mn activator.

The processes of tunneling and impact excitation are both very non-linear with respect to the applied field. These help give the luminance vs voltage variation and an unusually strong steepness and threshold behavior, thus greatly facilitating multiplexing (Fig. 3.6.3).

If one examines the "lighting" of a pixel under under high magnification, "filamentary conduction" is observed. As the field is increased to the point where the initial emission begins, it is seen that emission is not uniform, but that little streams (filaments) of light can be observed: some fixed, at the lowest threshold levels; some wandering, at slightly higher threshold points. As the voltage is increased, the pixel emits over more of its area and can appear mottled until the higher field causes the entire pixel to emit. If the applied voltage is a square wave with an extremely fast rise time, this phenomenon may not be observed. It can be assumed that since some non-uniformity exists in any pixel, some filamentary conduction will always take place at turn-on.

3.6.3 PHYSICAL CHARACTERISTICS

3.6.3.1 Size

The actual panel size of an ac TFEL is constrained by the need to provide a hermetic seal and electrical connections around the periphery. At least 1.0 cm must be provided to the length and width of the active area. The depth of panels is usually less than 1.25 cm. The addition of a Thin-Film Transistor (TFT) drive (See Section 3.6.4) will not appreciably affect the depth. However, if MOS circuity is rear-mounted, an additional 0.3 cm may be required.

3.6.3.2 Life Expectancy

Although "half-life" has often been used to describe the expected usefulness of flat panel displays, TFELs evidence a unique characteristic, due to "burn-in" or annealing. The annealing process probably results from a redistribution of luminescent centers. The burn-in establishes and maintains a higher luminance level than when first activated (Fig. 3.6.4)(3.6.18). Once established, this level can be maintained as a linear function by minor voltage adjustments, sometimes called maintenance or flat maintenance. Fig. 3.6.5 shows the effect on a device which had not experienced burn-in. Life tests have demonstrated that an MTBF of 10,000 hours is readily achievable.

3.6.3.3 Reliability

The reliability of ac TFEL devices not only depends on the quality of the polycrystalline manganese-doped ZnS layer, but the quality of the dielectric layers, as well. Since the light output of the device is directly proportional to the charge flowing through the capacitive layers per pulse, the number of pulses per second, and the voltage across the ZnS film, higher reliabilities can accrue if high dielectric constant and breakdown strength insulator films are used (3.6.19). Caution must be considered in the sealing of the sandwich, since the TFEL structure demonstrates considerable sensitivity to moisture (extreme in the cases which employ Y_2O_3 as a dielectric). The devices must be passivated in some way to avoid progressive destruction of the device through a process of area breakdown delamination, or peeling of the film. On the other hand, recent work by Suntola, using atomic epitaxy deposited thin-films, has evidenced structures so dense and uniform as to be seemingly insensitive to moisture and,except at the edges, to require minimal sealing (3.6.20). Small burn-outs can occur at pinholes in the dielectrics because of high current conduction. When the high current conduction occurs, the conductor acts as a "fuse" and the circuit burns open, thus limiting the degree of destruction. This fusing action is very helpful in the overall performance of the display since it blocks the possibility of catastrophic failure. The atomic epitaxy deposition appears to minimize, although not eliminate, this problem (3.6.20).

Another characteristic of thin-film EL devices is a relationship between localized failure mode and active device area, a relationship which is critically dependent upon the electrode materials and thickness, as well as upon the choice and perfection of the dielectric layers. Breakdown is a nonlinear phenomenon. Once initiated at some defect in the dielectric layer, the stored energy available to produce destructive local heating is proportional to the contiguous active device area. Unless the electrode restricts or constrains the lateral flow of energy, catastrophic failure may result. This is one of the major problems in this technology, because, considering the high fields involved, it is not yet feasible to make very large areas totally free of local breakdowns. Suntola has proposed slotting the electrodes at the line intersections as a means to control the lateral destruction (3.6.21).

Another important factor is the possible contamination of the materials. Efficient luminescence with an Mn^{+2} activator employs a ten times higher concentration than with Cu or Cl activators. The practical significance is that the Mn activated phosphor system is less affected by impurity contamination; i.e., given the same order of contamination.

3.6.3.4 Memory

A potentially useful memory effect has been observed in ac TFEL devices which have an appropriate thickness and manganese doping. When the applied voltage is first increased, the light output in a memory device increases nonlinearly as a non-memory device would (3.6.22); however, as the applied voltage is reduced, the light output tends to remain at a high level (which depends on the magnitude of the highest prior applied voltage). A memory display panel of 1248 characters (5x7) has been demonstrated (3.6.23). Using this effect, one can also obtain grey scale with memory by using (switching) voltage amplitude modulation in the matrix address mode. This hysteresis behavior can also be triggered by light as demonstrated by Suzuki et al (3.6.24). More recently, driving techniques have been developed such that an ac TFEL memory panel, operated as a video display panel, can have a stop motion or frame store capability (3.6.25). Furthermore, in a storage display mode, the information may be electrically read out by applying a reading pulse to sense the state of each cell (pixel) (3.6.26). The major importance of the memory effect is that it can significantly reduce the demand on the luminous efficiency of the ac TFEL device since it obviates the need for refresh. On the other hand, the long-life characteristics typical of the non-memory panel have not been demonstrated in the memory version. The stability of the memory operation is also one of the critical problems still under investigation.

3.6.3.5 Efficiency

The efficiency of the EL is strongly dependent on the Mn concentration. The efficiency of the driving circuitry must also be considered. Typical luminous efficiencies of ac TFEL panels are in the range of 1 to 2 lumens per watt, with values of 5 and 9 lumens per watt having been reported (3.6.21 & 3.6.27). At 2 lumens per watt, a 15 cm square panel, with typically 20% of that area in actual use, will consume about 185 mw for a 32 cd m^{-2} luminance (sufficient for sunlight legible alphanumerics and graphics, but not grey scale video). Since the line driver technology now being used can dissipate up to forty times that power, this can result in a total power consumption of as much as 7 watts. In essence, while display efficiency is obviously important, drive circuit efficiency is, at present, more important (See Section 3.6.4.3).

An offsetting characteristic of the thin-film structure which reduces efficiency is the large capacitance per unit area. Multiplexing, especially line-at-a-time matrix addressing, leads to drive waveforms with high frequency components. The large capacitance in the structure results in high displacement currents which add to the power dissipation in the drive system (See Section 3.6.4). Some of the more significant electrical characteristics are shown in Fig. 3.6.6.

3.6.4 ADDRESSING/DRIVING

3.6.4.1 Approaches

The ZnS:Mn EL film requires a large electric field to cause it to emit light. The electric field must be sufficient to cause filamentary conduction in the phosphor but not so high as to cause the encapsulating dielectrics to conduct. An ac field is necessary for sustained operation. Despite these requirements, the wave shape of the excitation signal is not usually critical. There are several ways to implement the required voltage drive:

a) At present, the most expeditious method is to use x-y matrix addressing and powering from the crossed grid, i.e., edge leads in combination with MOS drivers. This however, leads to a low duty factor for each element and lowers the luminance.

b) Another way is to use discrete transistors at each pixel. While offering 100% duty cycle, this method results in an extremely expensive and cumbersome display.

c) A third method is to integrate a thin-film transistor (TFT) at each pixel in an array using thin-film fabrication techniques. The advantages of this approach, and very significant, are that each pixel can be on with a 100% duty cycle and that resonant power supplies can be used to save the imaginary power and reduce the overall power consumption. The disadvantage of this latter approach is that, so far, the yield has been low due to the great number of process steps (approx. 11).

3.6.4.2 Matrix Addressing

The discrimination ratio (steepness of the luminance vs voltage curve) is 10^4-10^5, high enough to allow multiplexing hundreds of lines in a matrix display by the simple crossed grid approach. This fact has allowed successful demonstration of both graphic and video displays using this technology. However, luminance is limited by the duty cycle. The matrix usually consists of line and column electrodes with each intersection of the electrodes defining one pixel of the display (See section 2.2.3). Figure 3.6.7 shows an electrical model for a matrix EL display. The line and column electrodes are modeled as distributed resistances between each pixel. Each pixel can be modeled as an ideal capacitor in parallel with a non-linear resistor. The capacitance models the thin-film structure, and the non-linear resistor models the electrical effect of light being emitted by the EL phosphor. The effect of the non-linear resistor has a negligible impact on the entire circuit and is usually ignored for circuit analyses. Each pixel then, is represented by a single capacitance - Cp.

The image on an EL display is generated by programming the luminance of the individual pixels. The method associated with the programming of these pixels is commonly called the drive scheme, while the electronics needed to incorporate this drive scheme is the exerciser or generator. The exerciser electronics is divided into the logic and the high voltage drivers. The design of the logic is relatively straight forward with the vast source of microprocessors and integrated logic circuits available. The primary concerns for incorporating a drive scheme are the high voltage drivers and the interface of these drivers to the controller logic and the electrodes of the display.

There have been many drive schemes proposed for ac TFEL displays. All of them utilize the voltage luminance characteristics of the thin-film structure. Typical curves are shown in Figure 3.6.8. Most EL displays operate in a binary mode where a pixel is either on or off. Grey shading of the pixels can be done by operating at points along the voltage luminance curve.

A characteristic of the thin-film electroluminescent material is that it emits bursts of light, with each burst having an exponential persistence decay lasting about 3 m-sec (i.e., $L=e^{-1}$, with a decay to half brightness about 1.25 m-sec). Before a second burst of light can be activated, the ac TFEL material must be refreshed with a voltage pulse of the opposite polarity. Hence the drive of an ac TFEL display essentially requires an ac waveform. Also, because of this characteristic, the apparent luminance of the image on the display is dependent on the frequency at which each pixel emits the bursts of light.

The drive scheme pulses each pixel of the matrix display once per frame using a line-at-a-time addressing concept. By this means, the drive scheme steps through all the lines of the matrix display one at a time. For each selected line, the drive scheme lights each desired pixel along that line to the proper luminance and prevents all the other pixels in the display from lighting. The luminance of each pixel along the selected line is controlled through the corresponding column. Because of the matrix design of the EL display, all pixels are capacitatively linked; not only are the pixels along the selected line charged to a desired voltage, but all the pixels are charged to some degree. When these non-selected pixels are charged to a sufficient level to emit light, this is described as crosstalk. Eliminating this crosstalk is a principal requirement for the drive scheme.

To understand how a drive scheme eliminates crosstalk and achieves the desired image on the display, the network of capacitors representing the display can be simplified. Because of the line-at-a-time addressing and the binary operation of the pixels, the drive scheme interface to the display can be modeled as four leads. These are the selected lines, the non-selected lines, the selected columns, and the non-selected columns. The selected columns are defined by the columns corresponding to the pixels along the selected lines that are turned on. Likewise the non-selected columns are defined by the columns corresponding to the pixels along the selected line that are off.

Figure 3.6.9 shows the capacitive model for an ac TFEL display. N is the number of lines, M is the number of columns, and m is the number of lit pixels for the selected line. As shown, there are m pixels between the selected columns and the selected line and M-m pixels between the non-selected columns and the selected line. The pixel capacitances for the remainder of the display are lumped into two model capacitances. With the capacitive model, drive schemes can be analyzed and drive electronics optimized.

3.6.4.3 Drivers

Although line drivers have been made from available discrete components, they are expensive and bulky. Several high-voltage MOS electronic techniques developed recently may lead to low-cost line and column drivers for EL displays. One such MOS approach is "Diffusive Self-Aligned MOS (DSA-MOS)", a form of DMOS. A second MOS technique uses VMOS (3.6.28). Both N/MOS and P/MOS can be made by the VMOS process, which can be combined to form a "push-pull" amplifier for ac drive. The "push-pull" driver is a distinct advantage over the type of driver available from DSA-MOS. Drivers are now being developed which should reduce the line power consumption by a factor of 2, initially, and 5 or more, subsequently. Miller and Tuttle (3.6.29) have reported on resonant drive circuitry which, theoretically, can reduce the real power dissipation to less than 10% of the power now used. This, or the successful achievement of TFT or similar drive techniques which allow 100% duty cycle and low power with resonant drive, will make a major impact on the utilization of TFELs.

3.6.5 SYSTEM INTERFACE

Although the ac TFEL is digital in nature, one current approach to the implementation of ac TFELs is to consider the display simply as a display monitor, i.e., the signal input would be compatible with, for example, a U.S. standard television RS-170 or RS-232 composite video input; all conventional signal formatting, symbol generation, and conditioning, etc., to be handled externally to the display monitor. The display monitor will provide the proper decoding (timing, x and y sync strip-off, etc.) to match to the internal refresh and matrix addressing necessary for the display, itself. In this manner, the display monitor can be used as a direct replacement for a CRT. The other system interface considerations appropriate to the CRT as enunciated in Section 3.1 generally hold for the ac TFEL display monitor. Both low and high resolution graphic and video signals would be processed in terms of the actual display characteristics.

3.6.6 VISUAL CHARACTERISTICS

3.6.6.1 Reflectivity

Specular reflectivity associated with a front glass surface is essentially independent of the technology. The now standard treatment is to use a high efficiency reflection reducing coating, such as that described in U.S. specification MIL-C-14806. Since the front surface of the EL display is glass, the same coating requirements would prevail.

In general, for an excited TFEL element to be directly visible against its background, the reflection of ambient light must be minimized. Most conventional emitting display schemes employ filters to reduce the internal specular and diffuse reflectance. This, in turn, also interferes with the emission from the display by introducing optical attenuation. The high contrast dark field TFEL requires no filters, thus all the light emitted forward from the TFEL layer is transmitted without attenuation. Because of the high index of refraction the ZnS layer, about 2.3, only a small cone with an angle of rotation of about 18 degrees is not totally reflected.

3.6.6.2 Contrast

With a vacuum deposited thin-film phosphor structure, ambient light is effectively scattered, i.e., diffusely reflected, only at the rear surface of the phosphor, in the region designated by dielectric film #2 (See Figure 3.6.2). Ambient light arriving through the display structure can be absorbed here, if dielectric film #2 matches the index of refraction of the TFEL film and is opaque. Taking advantage of this situation, high contrast display structures with a diffuse reflectivity less than 1/4 of 1 percent (3.6.30 & 31) were achieved. More recently, black layers measuring between 0.1 and 0.14% reflectivity have been demonstrated (3.6.32). Because very high contrast ratios can be obtained with a black layer, TFELs are readable in sunlight levels beyond 10^5 lux. As a specific example, a black layer TFEL display having a diffuse reflectance of 0.1% would reflect a 3.2 cd m^{-2} in a 10^5 lux ambient. If the display element (pixel), itself, emitted about 6.4 cd m^{-2} the contrast ratio would be the 6.4 emitted, plus the 3.2 reflected, divided by the 3.2 reflected off the black layer or $(6.4 + 3.2)/3.2 = 3$. Obviously, higher outputs will provide more than adequate contrast.

Thin-film EL alphanumerics have been demonstrated as more legible than comparable dot matrix CRT formats because of the sharp, square-dot pattern, though this has not been extensively tested (3.6.32). The practical grey scale range currently depends on the number of lines multiplexed and the ambient illumination. The inherent nonlinearity and the peak luminance does allow refresh matrix operation up to 500 lines with about 10-15 cd m^{-2} luminance and negligible loss of contrast due to crosstalk. However, if a display is a large area, the peak currents will be large, and beyond 30 cm square, one must look more closely at the properties of the transparent electrode material to avoid waveform distortion in the interior of the panel. If the TFT approach or an equivalent process proves successful, not only would this problem be obviated, but luminance levels of up to 200 cd m^{-2} could be easily obtained.

3.6.6.3 Flicker

Flicker is easily detectable when a TFEL pixel is refreshed at below 50 Hz, although flicker or "strobing" can also occur under high vibration at higher refresh frequencies. The persistence of the phosphor is relatively independent of the current. Normally operated ac TFELs otherwise exhibit no flicker.

3.6.6.4 Resolution

Resolution, once a serious problem, is no longer a limiting factor. A panel with a density of 200 lines per cm across a linear dimension of 2.54 cm has been demonstrated (3.6.33) for use in a helmet-mounted display as well as a 512 by 640 line display at a density of 40 pixels per cm (100 pixels per inch) (3.6.34). The latter would appear to satisfy most graphics and video requirements. Line and column drivers are being developed to utilize the capability of these panels. The ultimate resolution is probably limited by the size of the pinhole destruction phenomenon (3.6.35).

3.6.6.5 Color

Work on color has not been extensive. Soxman et al, made a number of samples yielding green, yellow, orange and red (3.6.36). Probably because of other deposition problems, these samples demonstrated low luminance, efficiency and life. More recently, other work has been reported with better results (3.6.37 thru 39). For example, Hale reported a green output of over 300 cd m^{-2} (3.6.37). Work in color was also reported by Chen (3.6.40). Examples of colors achieved by using rare earth activators are: white (P_rF_3); blue/green, yellow, and red (D_yF_3); blue (T_nF_3), Green (T_bF_3), blue (E^3F_3) and red (E^2F_3).

At the present time, the only color which is produced with good efficiency in thin-film EL devices is the yellow with a wavelength spectrum of light emission approximately 50 nm wide at half luminance and centered at about 585 nm at about 5 lumens per watt. While other colors can be produced by ZnS with rare earth dopants, the best, so far (green), has yielded an efficiency of less than 0.5 lumen per watt. This is a drawback which may have some fundamental basis in the nature of rare earth electron configurations in ZnS. Further studies are expected to shed more information/this matter. Like the manganese, the emission is relatively independent of temperature and frequency. This is a very important consideration for matrix addressed displays operating over a wide temperature range such as for military applications, particularly since many frequency components are present in matrix addressed systems.

3.6.6.6 Viewing Angle

Viewing angle, often a critical factor, such as in liquid crystal displays, is not a concern with TFELs. The image can be seen almost to ± 90 degrees although the practical limit for alphanumerics and complex graphics is probably only useful to about ± 70 degrees.

3.6.7 OTHER EL DEVICES

3.6.7.1 AC Powder EL

AC Powder EL is the historical variety associated with Destriau, the object of an enormous research effort in the 1950's and early 1960's aimed (unsuccessfully) at making it an efficient source of illumination, and well described in a book by Ivey (3.6.41). The active layer, which consists of a suitably doped ZnS powder (5-20 m grains) suspended in a dielectric, is sandwiched between two electrodes, one of which is transparent, and is supported by a substrate. The substrate may be glass, flexible plastic, or may be a metal such as aluminum. In the latter case, the top electrode must be transparent. The dielectric may be organic (e.g. cyanoethyl cellulose) or a low melting point glass. A second dielectric is often used as extra protection against catastrophic dielectric breakdown. Applied fields of 10^4-10^5 V cm^{-1} are sufficient to produce luminance as high as 340 cd m^{-2} at efficiencies which are reasonable by display standards (1-5 lumens per watt). Luminance increases with frequency at moderate frequencies (100-10^4 Hz), but device life is usually decreased in the same proportion. One has a choice of colors depending upon the activation of the ZnS powder. Copper is always used in these EL powders. The combination of Cu and Cl can give either blue(460 nm) or green (≈510 nm) emission, depending upon the relative amount of Cl, while the combination Cu, Cl and Mn yields yellow (≈585 nm).

Empirically, a key parameter is particle size, which is involved in some critical tradeoffs. Small particle size increases efficiency and nonlinearity, but decreases life. Efficiency generally has the functional form $L^{1/2}V^2$ (where L is luminance) and usually peaks well below the highest luminance levels; this ultimately relates back to particle size which is increased to improve life, yet decreased to improve luminance, nonlinearity and efficiency.

Much of the behavior can be understood if one looks at the microscopic nature of the Destriau phenomenon. The best synthesis of observations and ideas on this subject is the work of Fischer (3.6.42). EL powders are typically fired at high temperatures where the hexagonal phase predominates. When they are cooled, there is a transformation to a cubic zinc-blend structure, and the copper (previously mentioned as essential), which exceeds the solubility limit, precipitates on defects resulting from the hexagonal to cubic transformation. The result is imbedded Cu_xS conducting needles which act to concentrate an applied electric field at their tips. Thus an applied field of 10^4-10^5 V cm^{-1} can induce a local field of 10^6 V cm^{-1} or more. This is enough to induce tunneling of holes from one end of the needle and electrons from the other. The holes are trapped on Cu recombination centers, and upon reversal of the fields the emitted electrons recombine with the trapped holes to produce light. Larger particle sizes lead to longer needles and greater field enhancement, but as the shunted material still contributes to the losses, efficiency is reduced. In addition, the localized current flow results in localized heating. This, together with the high fields, can result in diffusion and electromigration of active species such as Cu^{+2} or harmful sulfur vacancies which interfere with the emission process. The Lehmann (3.6.43) hypermaintenance process was, in fact, an attempt to reduce and control sulfur vacancies, which also affect the mobility of Cu ions. Since moisture is thought to be a source of sulfur vacancies at the particle surfaces, Fischer et al (3.6.44) proposed that phosphor particles should be microencapsulated with a phosphosilicate, after Lehmann-type processing, to yield even longer life. The longer life associated with larger particle diameter is related to a longer diffusion time for defects generated at the surface of the grains. Life is still a key problem for the application of this technology, but there is indeed some expectation for more than 10,000 hour life at moderate luminance, especially for green-emitting devices. The problem is that peak luminance is a serious limitation, and low duty cycle operation is not acceptable. This is especially important because the powder reflects ambient light, and good contrast is achieved by the use of an absorbing filter on the front of the display, as in a CRT display. These absorbing filters, however, seriously reduce the emitted light.

The most promising approach to using ac powder EL in complex displays is in conjunction with arrays of thin film transistor (TFT) circuits. Several groups pursued this approach (3.6.45-47) with the most impressive results obtained by Brody et al (3.6.45). Currently, ac powder ELs are used in some civil aircraft control panels for night illumination and are being tested for use in military aircraft as well, particularly because of the need for compatibility with night vision goggles. These displays, however, cannot satisfy the high luminance aircraft environment.

3.6.7.2 DC Powder EL

There is another type of powder EL device which is associated primarily with A. Vecht and his collaborators (3.6.48 & 49). In the ac powder case, the high temperature firing and cooling results in a conducting Cu_xS surface layer on the particles, which is removed chemically. In the dc powder case, a fine grain (0.5-1 μm) Mn-doped ZnS powder is prepared with Cu_xS coating, and a layer of the powder (with a small amount of binder) is formed into the device. If a matrix display is being fabricated, the powder layer, which is 40-50 μm thick and is conducting, must be patterned into strips so that there is no shorting from line to line. Such a device must be "formed". When a voltage is first applied, a large current flows, the layer heats up, and gradually a narrow region about 1μm thick, adjacent to the SnO_2 anode, begins to luminesce. In the standard ZnS:Mn device, the light is yellow (585 nm), characteristic of Mn emission in ZnS.

There are three points to be made regarding this structure. First, the general requirement that the thick powder layer be patterned, limits the resolution which one can easily achieve relative to thin-film structures and even relative to ac powder structures. Second, this structure, by itself, provides no protection for the phosphor powder; thus it must be hermetically sealed. Since one is dealing with a white powder device viewed through the glass substrate, good contrast in high ambient illumination is at the expense of device luminance, i.e., system efficiency. One valuable characteristic of dc powder devices is that they can be operated in a pulse mode beyond the voltage and luminance of the forming condition,and the net effect is a better discrimination ratio and average luminance than one might have expected from the dc characteristic (3.6.50).

Luminance maintenance seems to be a somewhat complex question for these devices. There is no simple functional form for the decay; although pulsed operation, in particular, and low luminance operation, in general, lead to longer life. Devices operated at 8 cd m^{-2} (pulsed) can be expected to retain more than half their initial luminance for more than 10,000 hours in the best cases. Recently, Alder et al, (3.6.51) reported good quality panels with mean luminance values of between 175 and 350 cd m^{-2} and a half-life luminance of 3000 hours.

An interesting application of dc powder is the alphanumeric matrix display development first reported by Mears et al (3.6.50), taking advantage of the unique pulse response characteristics. While the initial report described a 36 character display, they also discussed the capability for increasing the size to a 200 line display of 1250 characters, which they subsequently achieved (3.6.52). Other mechanizations and interface electronics were discussed by Smith and Werring (3.6.53)

Much of the recent work in this technology has been aimed at extending the available color range by using different powder materials and different activators. DC electroluminescence has been demonstrated for various rare earths in ZnS and for Mn in Ba_2ZnS_3 (3.6.54) as well as for a number of alkaline earth sulfides doped with rare earths (3.6.55 & 56). Most of these alternatives have been much less efficient than ZnS:Mn, Cu, but recent results are encouraging; for example, ZnCaS:Ag produces green (70:30) and red (30:70) emissions which are almost one third as efficient as the standard yellow phosphor. There is also a fairly good blue-green (SrS:Ce, Cl) phosphor. Most important is the steady rate of progress in these new EL materials, which may stimulate renewed interest in this technology, especially where a range of colors is important. DC powder ELs are being used in several applications where the luminance environment is controlled. However, as in the case with the ac powders, these displays will not meet the high illumination aircraft environment.

3.6.7.3 DC Thin Film EL

The simplest electroluminescent structure one can conceive of is a thin-film of phosphor with electrodes on both sides driven by a dc source. This is probably the reason why the intuitive urge to exploit the phenomenon had so often led people in this direction. Attempts to make devices of this sort go back many years, and the materials most often used are the familiar ones, ZnS:Mn, ZnS:Cu,Cl, and ZnS:Mn,Cu (3.6.57-61). The basic problem with thin-film devices excited by dc voltages has been a tendency toward catastrophic failure, especially in the case of films without copper. For devices employing ZnS:Cu,Mn, there is at least one layer of Cu_xS adjacent to the phosphor film. It appears that in the absence of copper, or for low concentrations of copper, the fields required to initiate luminescence are so high that avalanching takes place, leading to negative resistance and a runaway current. A resistive layer stabilizes the current distribution. When Cu_xS is present, not only can lower fields be used, but very likely, the recombination of Cu sites suppresses space charge formation and negative resistance effects. (Films, with copper, can, under ac excitation, behave analogously to ac powders (3.6.62) and probably involve alternate injection of holes and electrons from Cu_xS.)

A variety of luminance-voltage dependencies have been reported for dc thin-film devices, but the common characteristic is a greater nonlinearity than is typical for ac powders. The most interesting recent work in the ac film area has been that of Abdalla and Thomas (3.6.63). This device seems to be a direct film analog of the dc powder device of Vecht et al (3.6.49), with a Cu_xS injecting layer and a copper-free active layer being created during the forming process. As with dc powder devices, it works best in the pulse mode, which apparently allows the high fields necessary for impact excitation of manganese without excessive heating. Under these condition, they reported good maintenance.

Further performance data was provided by Abdalla et al, at the 1980 IEEE-SID-AGED Biennial Display Conference (3.6.64 & 3.6.65). Similar structures were reported by Vlasenko and Gergell (3.6.66), but no indication of device life was given. Finally, there are reports of dc electroluminescence of reasonable efficiency in films of other materials, such as CdF_2, and La_2O_3, but neither of these appears to be suitable for practical use at this stage; CdF_2 films are not sufficiently stable, and La_2O_3 has low luminance output.

3.6.8 STATE OF DEVELOPMENT

It can be concluded that each of the four types of electroluminescent displays may find useful commercial and industrial application. Military applications, however, are more stringent. In the case of ac powder devices, if the applications are to go beyond the simple direct address displays (or lamps, as they are commonly called), it is important that good TFT arrays be developed. If that should occur, the ac powders may prove to be useful, albeit limited luminance. Ac powder devices have been proposed for night lighting in military vehicles where night-vision goggles are to be used. The dc powders now appear to have enough life to be useful and are being exploited for several applications in the U.K.; they have the drawback of all matrix displays - high drive cost, but like the ac powders could be used in limited airborne applications, such as for night lighting at low illumination levels. The principal advantage presently seems to be the variety of colors which can be provided. Dc films are also achievable; they can be driven with a relatively low voltage and used at room temperature. Nevertheless, considerably more development must take place before they will be competitive with the powders.

The ac thin film EL devices are still the most interesting for military airborne display applications because of their many attractive features: high peak luminance, long life, nonlinearity, contrast, memory, and currently, a high probability to provide several colors. Nevertheless, matrix displays will not find wide application without reduction in drive costs.

The following high-contrast ac TFEL devices represent a few devices being developed for military airborne application.

a) A low cost, end buttable, seven-segment, two digit display, with drive electronics, mounted on a standard dual-in-line package (DIP).

b) A 40 pixel cm^{-1}, 512x640 line, matrix display, capable of complex graphics and video, with rear mounted drive electronics, capable of at least 7 video levels at 10^5 lux ambient.

c) A 13 pixel cm^{-1}, 16 x 29 line discrete, with rear mounted drive electronics, for use as a 10 alphanumeric character indicator or multi-legend display switch.

For military airborne applications, legibility in high ambient illumination is not a wish, but a requirement. As suggested at the beginning, ac thin-film EL devices show the greatest promise for exploitation, particularly in the case of direct view dynamic displays presenting vector graphics and video information. It would appear that production devices and compatible drive circuitry are at hand and may soon be available for integration into military airborne subsystems (See Chapt. 4)

The above mentioned 512 x 640 line display measures 13 x 16.25 cm. Theoretically, the size is limited by the size of the vacuum chamber; in practice, a 30 x 30 cm display, now in development, probably represents a practical limit. However, most aircraft applications could be satisfied by the present state of the art (approximately 20 x 20 cm.).

Not included under reliability is suviveability. Because the structure is basically solid-state, vibration and shock are not critical concerns. Since the substrate is a glass plate, the usual precautions for glass must be taken.

Finally, as indicated in 3.6.3.5 and 3.6.4.3, power dissipation is principally contributed by the drive system. Nevertheless, the estimated power requirement for the 512 x 640 display, including the drive system, is under 20 watts.

3.6.9..ACKNOWLEDGEMENTS

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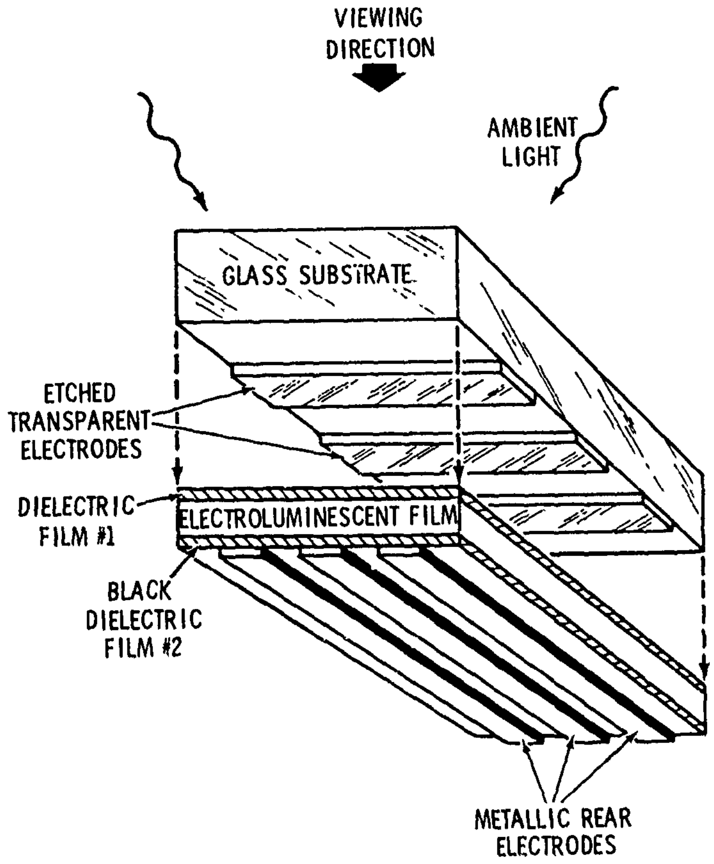


Fig.3.6.1 Schematic representation of a three layer, ac coupled ZnS:Mn thin-film device employing two transparent dielectric layers

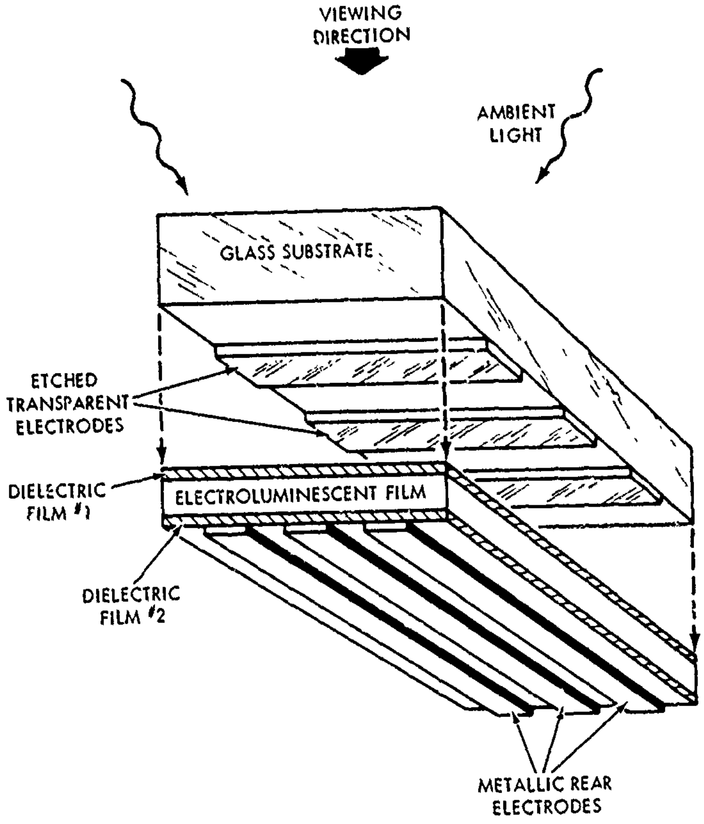


Fig.3.6.2 As Fig.3.6.1 but with a black light-absorbing rear dielectric film

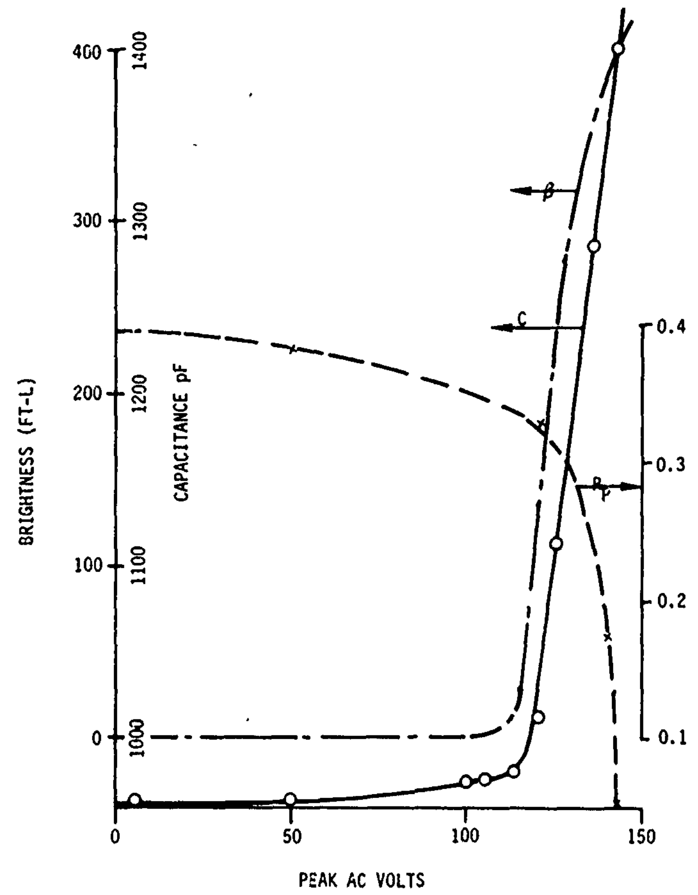


Fig.3.6.3 Typical luminance versus voltage curve showing the steep ac TFEL characteristic

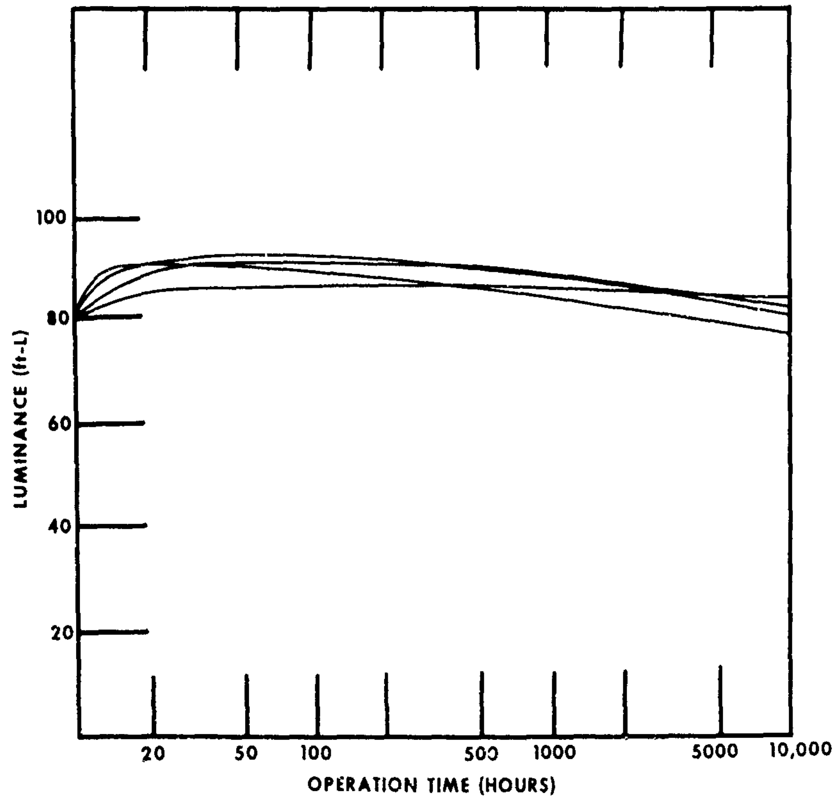


Fig.3.6.4 Improved luminance effect of burn-in of an ac TFEL resulting in a high maintenance profile

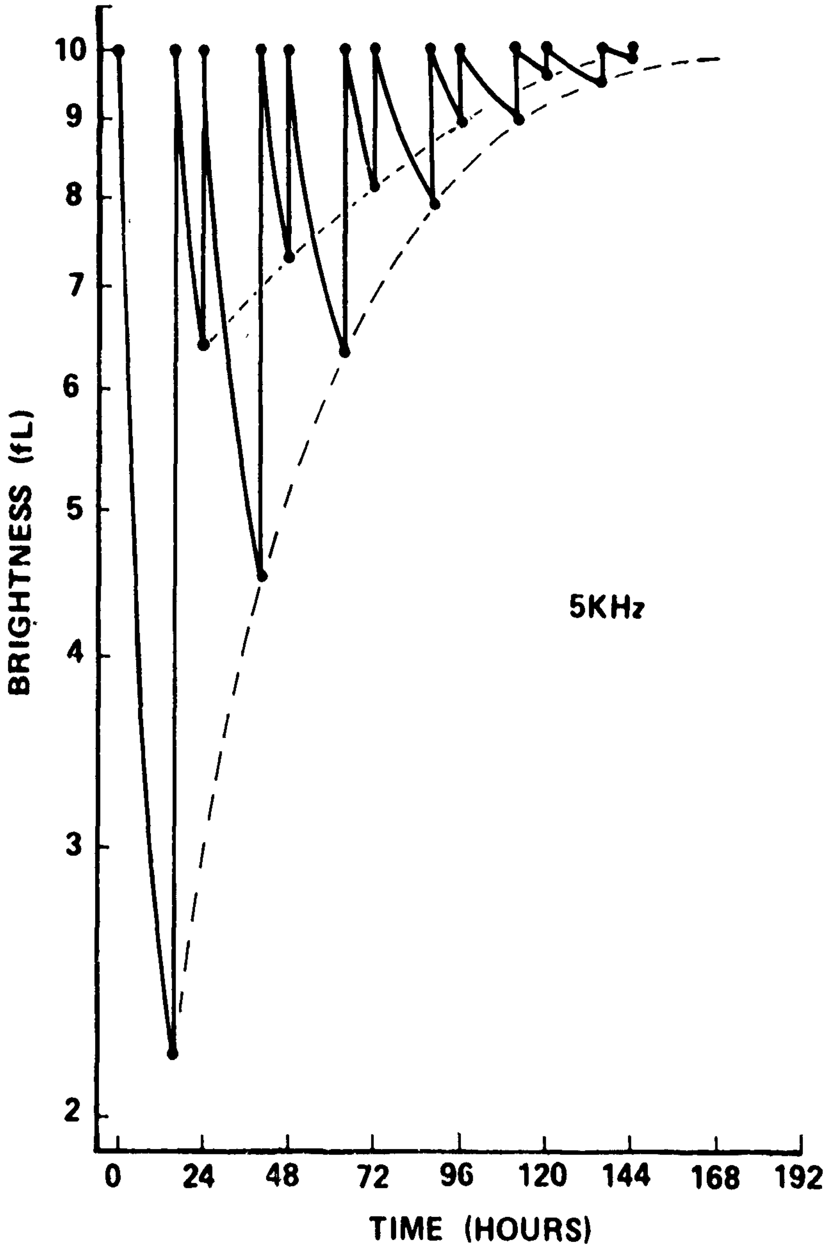


Fig.3.6.5 A short term typical flat maintenance curve resulting from periodic voltage adjustment

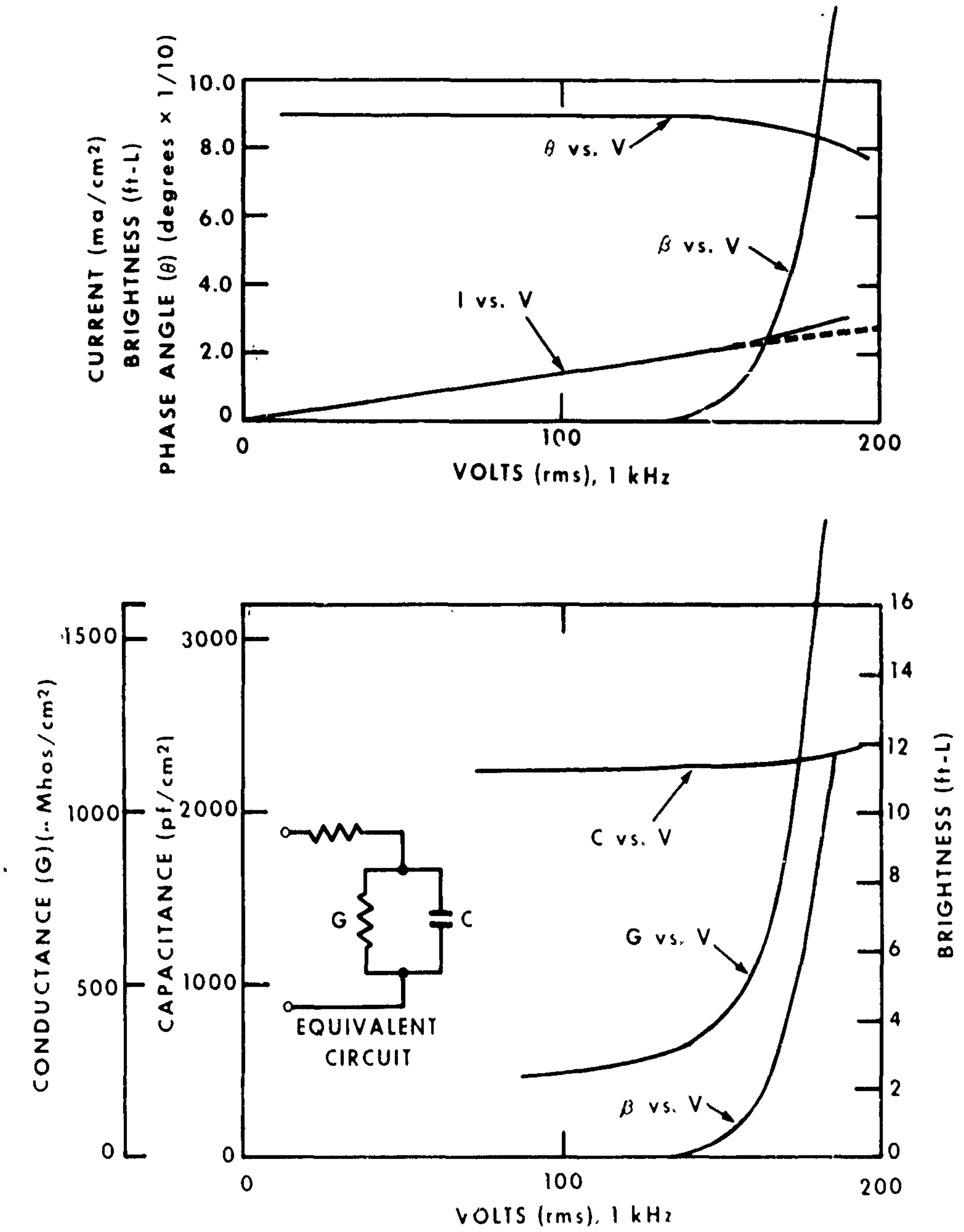


Fig.3.6.6 Electrical circuit characteristics of an ac TFEL display

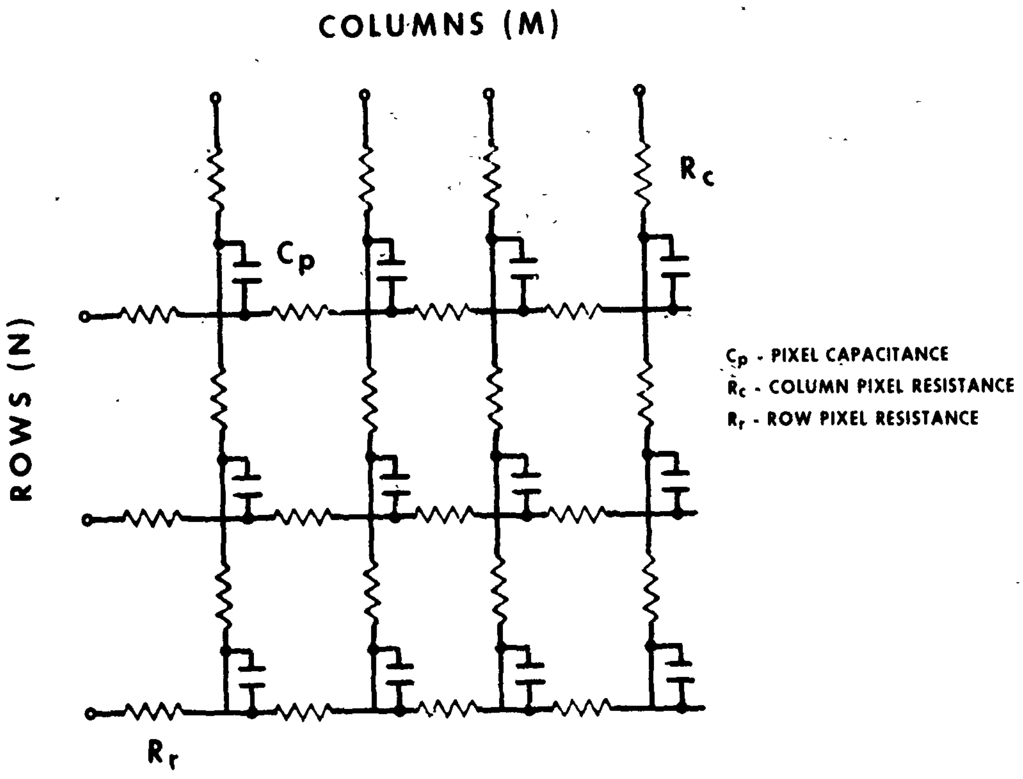


Fig.3.6.7 Electrical model of a matrix TFEL display

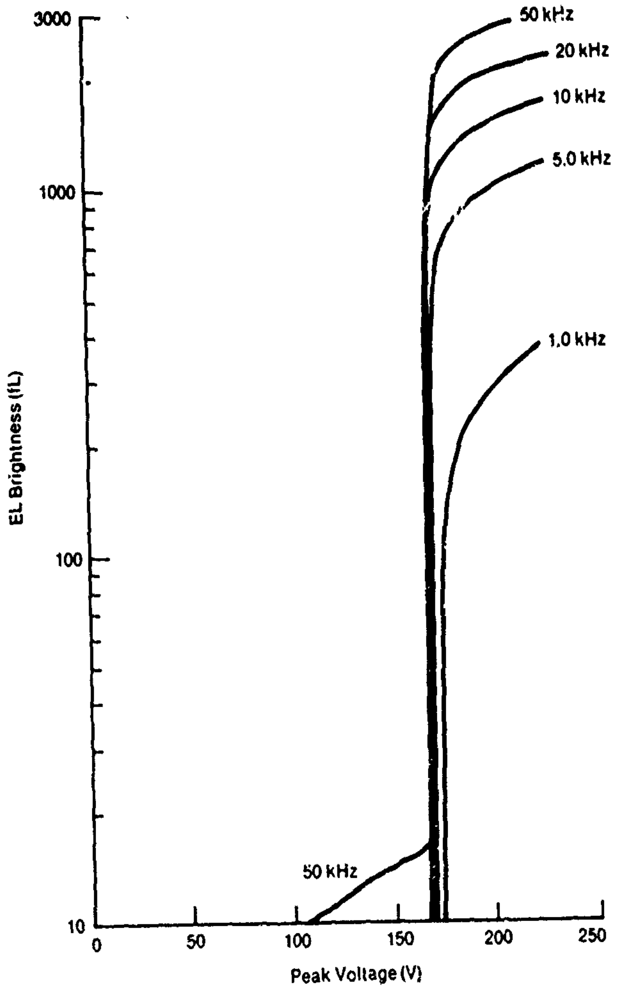
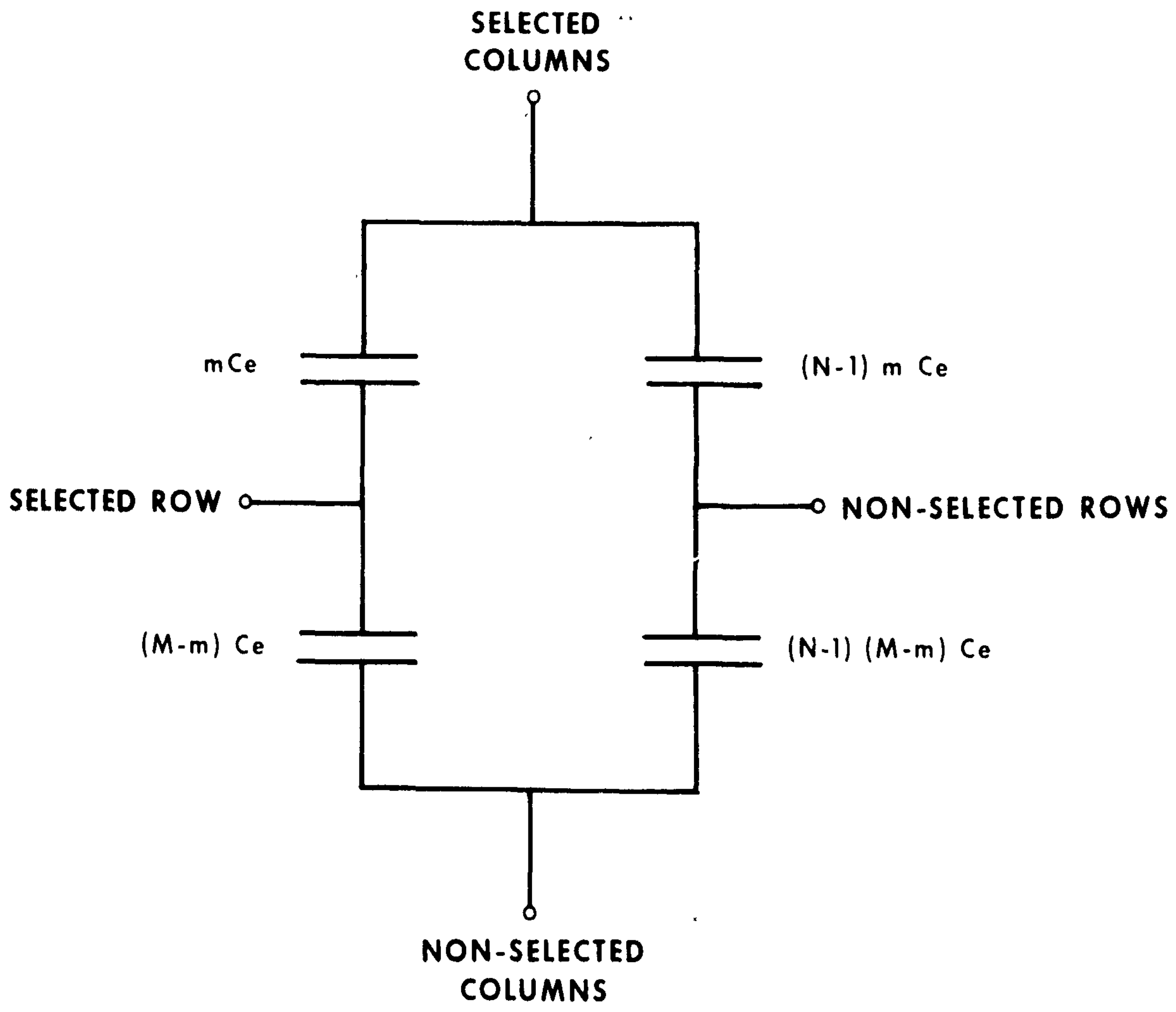


Fig.3.6.8 Typical steep luminance versus voltage curves



M - NUMBER OF COLUMNS
N - NUMBER OF ROWS
m - NUMBER OF SELECTED PIXELS PER SELECTED ROW
Ce - PIXEL CAPACITANCE

Fig.3.6.9 Capacitive model of a matrix ac TFEL display

3.7 ELECTROCHEMICAL DISPLAYS

3.7.1 HISTORICAL SURVEY

The rapid progress in the field of modern microelectronics has caused an increasing interest in information displays with low addressing voltages and low power consumption. These demands are satisfied by passive (i.e. non-emissive) displays. Such displays show - within certain limits - a luminance that is self-adjusting to the ambient light, but need an additional illumination in the dark. The most advanced displays of this kind are liquid crystal displays, which have been developed since the early 1970's and are being produced in large quantities.

The search for other materials and electrooptic effects for use in passive displays has been stimulated by two weak points of some liquid crystal displays: the angular dependence of the contrast and the relatively low background luminance in the case of black symbols on bright background due to the polarizers needed. A group of new technologies is represented by the electrochemical displays: electrochromic (ECD), electrodeposition or electrolytic (EDD) and electrophoretic (EPD) displays. The features of these three technologies look very promising: no angular dependence of the contrast, no need of polarizers and an inherent storage effect. However, the state of development is considerably behind that of liquid crystal displays and the produced quantities are rather small up to now.

3.7.2 PRINCIPLES OF OPERATION

Electrochemical displays like ECD, EDD and EPD all have in common that the contrast is achieved by a charge transport mechanism. The display panel is essentially an electrolytic cell consisting of a transparent front electrode on glass substrate, a back electrode and a suitable electrolyte in between.

In the case of ECDs, the front electrode consists of the electrochromic material used which is deposited on a glass substrate with transparent contacts (e.g. ITO-layer). The electrochromic material changes colour as the result of a certain charge transport. In EDDs, a thin light absorbing metallic film is deposited by the electric current on the transparent front electrode. The light absorption is due to a strong light scattering by the metallic grains of the film. EPDs use a coloured electrolyte. It contains suspended charged particles of different colour which move to the front electrode under the influence of an electric field. The incident ambient light is scattered or absorbed by the particles.

All three types of displays can reversibly be switched between three modes: "Write", "erase" and "memory". In the "write" mode, the information is given by colouration or deposition at the transparent front electrode. "Erase" is achieved by reversing the applied voltage. In the "memory" mode, the actual state is preserved even when the voltage is switched off.

3.7.2.1 Electrochromic Displays (ECD)

ECDs utilize the effect that certain materials change their optical absorption coefficient under the influence of an electric field or current in a reversible way. This change of the absorption power is perceived by the human eye as a colour change. Depending on the material used, the appearance can be switched from colourless (transparent) to coloured or from one colour to another one. The advantages of electrochromic effects are the potentially large luminance of the background (contrary to LCDs no polarizers are needed) and the angular independent contrast. Appropriate materials are various inorganic and organic compounds (3.7.2; 3.7.3). In the case of inorganic materials, the main interest of current work is concentrated on tungsten oxide (WO_3) (3.7.1; 3.7.4) and - to a lesser extent - on iridium oxide (IrO_2) (3.7.5), while in the case of organic materials, viologenes and rare earth diphtalo-cyanines are most promising (3.7.6).

The principal structure and operation of an ECD with tungsten oxide is explained in Fig. 3.7.1.

An ECD is essentially a galvanic cell consisting of front and back electrode with a solid or liquid electrolyte in between. The front electrode consists of the electrochromic material used (in this case WO_3) which is deposited on a glass substrate with transparent contacts (e.g. ITO-layer). In the case of ECDs on the basis of tungsten oxide, an approximately 0.5 µm thick layer of tungsten hydroxy-oxide is deposited by thermal evaporation of WO_3 in high vacuum. Various materials can be used as back electrode, e.g. graphite, metal (gold) or again tungsten hydroxy-oxid (so-called symmetric cell). In most cases $LiClO_4$ in organic solvents is used as electrolyte. In order to get an optimum appearance of the display cell, a contrast medium (e.g. white TiO_2 pigment) is added to the electrolyte (so-called reflective cell)(3.7.1; 3.7.3; 3.7.4).

The colour change of tungsten oxide ECDs is obtained by an electron-cation injection induced by an applied electric current. This mechanism provides an inherent memory. The following modes of the electrochromic cell are possible:

a) Write: An electric current flows through the cell with the front electrode as cathode. The tungsten oxide is transformed to a deep blue coloured tungsten bronze by a simultaneous injection of electrons Li^+ ions

$$\underset{\text{(colourless)}}{xe^- + WO_3 + xLi^+} \rightarrow \underset{\text{(blue)}}{Li_x\,WO_3}$$

The blue colouration is caused by the optically induced electron transition between the newly generated W^{5+} and the W^{6+} centers (absorption maximum at 950 nm). The switching time is of the order of 100 msec. A charge of typically 5 mC cm^{-2} has to be transferred in order to obtain a sufficiently high contrast.

b) Erase: A current flows through the cell with the front electrode as anode. The number of W^{5+} centers is reduced by the extraction of electrons out of the front electrode, thus transforming to the colourless state. Again the switching time is of the order of 100 msec.

c) Memory: When the current loop is interrupted, the instantaneously reached state remains. Storage times of several weeks can be easily obtained for the blue state. The memory effect is of great interest not only with respect to the balance of energy but also for saving the information in case of power failure. The information is not only preserved visually but can also be read out electronically from the state of the potential.

With some organic materials like diphtalocyanine complexes of rare-earth metals, it is possible to show various colours (red, green, blue, purple) with variation of the voltage applied. The compound is deposited by sublimation on the front electrode as a thin (200 nm) layer (3.7.6).

3.7.2.2 Electrodeposition Displays (EDD)

The principle mechanism in EDDs is the electrodeposition of a metal film on the transparent front electrode. Incident light is absorbed by the metal film. Erasure is achieved by applying a voltage with reversed polarity. Such a system has an inherent memory. These displays are also referred to as electroplating or electrolytic displays (3.7.7; 3.7.8; 3.7.9).

Similar to an ECD, the EDD represents an electrolytic cell (see Fig. 3.7.2). A suitable system consists of a transparent SnO_2 electrode and a metallic silver counterelectrode. The liquid electrolyte contains silver ions (e.g. AgI in methanol). A voltage between

0.5 and 0.8 V is necessary for a reversible electrochemical deposition of a silver film on the transparent electrode (cathode): "write". A thickness of 5 nm to 15 nm of the silver film is sufficient to get an optical density of 0.3. This high absorption is due to a strong light scattering by the silver grains. The layer has a grey to black appearance. By reversing the polarity of the electrodes (front electrode as the anode) the silver layer is dissolved: "erase". Switching times range from 50 to 300 ms. A charge transport of 5 - 10 mC cm^{-2} is necessary for one cycle.

When the current is interrupted, the actual state is preserved: "memory". The contrast depends on the quantity of the deposited metal thus providing the possibility for a continuous gray scale.

The contrast can be enhanced by adding an appropriate colour to the electrolyte or by using a coloured back electrode.

3.7.2.3 Electrophoretic Displays (EPD)

With EPDs, the contrast is achieved by a charge transport mechanism, like with ECDs or EDDs. However, no ions but charged macroscopic particles are transported (3.7.10.; 3.7.11.; 3.7.13).

The electrophoretic cell consists of two electrodes (see Fig. 3.7.3), the front electrode being transparent.The electrolyte is coloured and consists of a suspension of solid particles. Under the influence of an electric field the particles move to the front electrode and the colour of the particles is seen: "write". By applying a reversed voltage the particles move to the counter electrode and become invisible: "erase". The response time depends on the suspending medium, cell thickness, pigment particles and the applied electric field. Typical values are in the order of 10 msec. To reach an acceptable contrast, a surface charge density in the order of 0.1 μC cm^{-2} is required.

The display area free of particles appears in the colour of the coloured electrolyte. The particles stay at the electrode even if the electric field is switched off: "memory". Thus an inherent memory is provided. The persistance time ranges from several minutes to several months, depending on the materials used.

In addition, the electrolyte contains compounds which cause a spontaneous negative charge of the colloidally suspended particles and stabilize the suspension against sedimentation. These stabilizers are surfactants dissolved in the electrolyte and adsorbed onto the particles. Since the memory mechanism is related to interparticle and particle/electrode attractive forces, the storage time can be adjusted by the type and amount of surfactants.

Compared with ECDs and EDDs, EPDs require considerably higher addressing voltages (30 V and higher).

3.7.3 ADDRESSING

ECDs and EDDs operate at very low addressing voltages in the order of 1 V. Compared to LCDs the addressing electronics is more expensive since the cells must be protected against destroying by overdrive. However, the problems can be solved by the modern microelectronics.

The requirements for addressing EPDs are higher since much higher voltages are needed.

All three types of displays have addressing characteristics without a pronounced threshold. Therefore direct matrix addressing is not applicable. However, in some EP materials with very strong interparticle attractive forces, threshold effects have been observed (3.7.11), and matrix addressing seems to be feasible (3.7.12; 3.7.14). But the results are not satisfactory yet. The same holds for the introduction of a set of control grid electrodes in the EP cell which induces a threshold, thus enabling matrix addressing in principle

(3.7.14). The most promising technique to realize ECDs, EDDs or EPDs with high information content is by using an active transistor or diode matrix that is integrated in the display panel. However, the limited availability and high cost of such arrays have thus far allowed only laboratory demonstrations.

3.7.4 VISUAL CHARACTERISTICS

ECDs, EDDs and EPDs are passive, i.e. non-emissive displays, like LCDs. All three kinds of electrochemical displays are mostly used in the reflective mode. The information is displayed by the contrast between scattering and absorbing areas: ECDs and EDDs usually show dark information on bright background, while EPDs show bright information on dark background. However, it is possible to drive EDDs in the reverse mode, i.e. bright information on dark background. In addition, EDDs may be used with transparent electrodes and a coloured layer outside the cell or integrated in one of the substrated glass plates in order to display coloured information on a coloured or neutral background. Compared to LCDs, the reflectivity of the bright areas is higher since no polarizers are needed, and the contrast does not depend on the viewing angle. Typical contrast values are 1:10 and higher.

The spatial resolution of ECDs and EDDs is limited only by the structure of the electrodes, therefore it is very high: in the order of 100 lines mm^{-1}. EPDs have a lower resolution: typical values are in the order of 4 lines mm^{-1} for a 50 µm thick cell.

3.7.5 STATE OF DEVELOPMENT

Electrochemical displays are in a state of advanced laboratory development. Although there is no large series production yet, ECDs on the basis of tungsten oxide as well as EDDs are being produced in small quantities. The problems concerning practical applications are presently the lifetime which is still limited by chemical and electrochemical side reactions. An additional problem is the lack of a sufficiently high threshold in the electro-optical characteristics which is a prerequisite for multiplexed addressing (matrix addressing). Therefore, only alphanumeric displays are feasible as yet unless additional nonlinear elements are integrated in the display cell.

The chemical stability of the electrodes and of the electrolyte has to be improved. In the case of EPDs the remaining problems to be solved are mainly to develop more stable suspensions less prone to sedimentation of the particles.

Typical characteristics of electrochemical displays:

	ECD	EDD	EPD
operating voltage	0.5 - 2 V	0.5 - 2 V	30 - 100 V
electric charge/cycle¹)	5 mC cm^{-2}	5 mC cm^{-2}	0.1 µC cm^{-2}
contrast	5 : 1	10 : 1	40 : 1
response time ¹)	100 msec	100 msec	10 msec
memory	yes	yes	yes
temperature range	-20 °C to 80 °C	-40 °C to 80 °C	-20 °C to 80 °C
lifetime (room temperature)	10^7 cycles	10^7 cycles	10^7 cycles
matrix addressing	difficult	difficult	difficult

¹) depending on contrast desired

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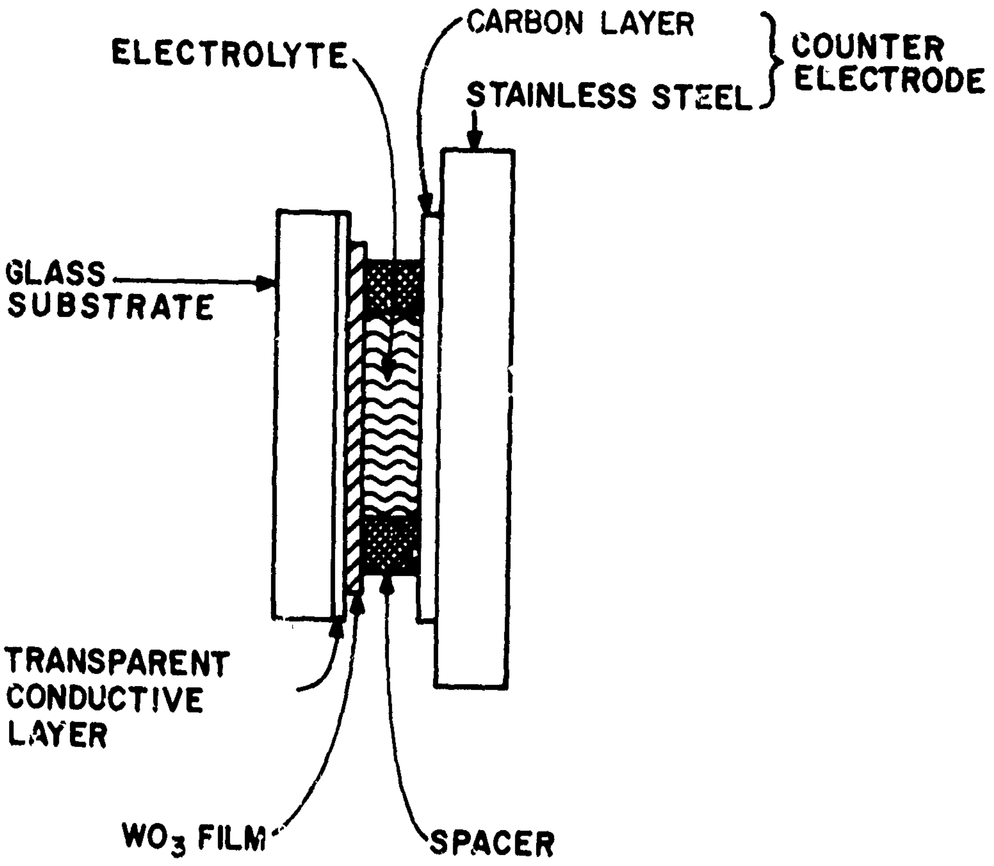

Fig.3.7.1 Typical structure of an electrochromic display (after 3.7.1)

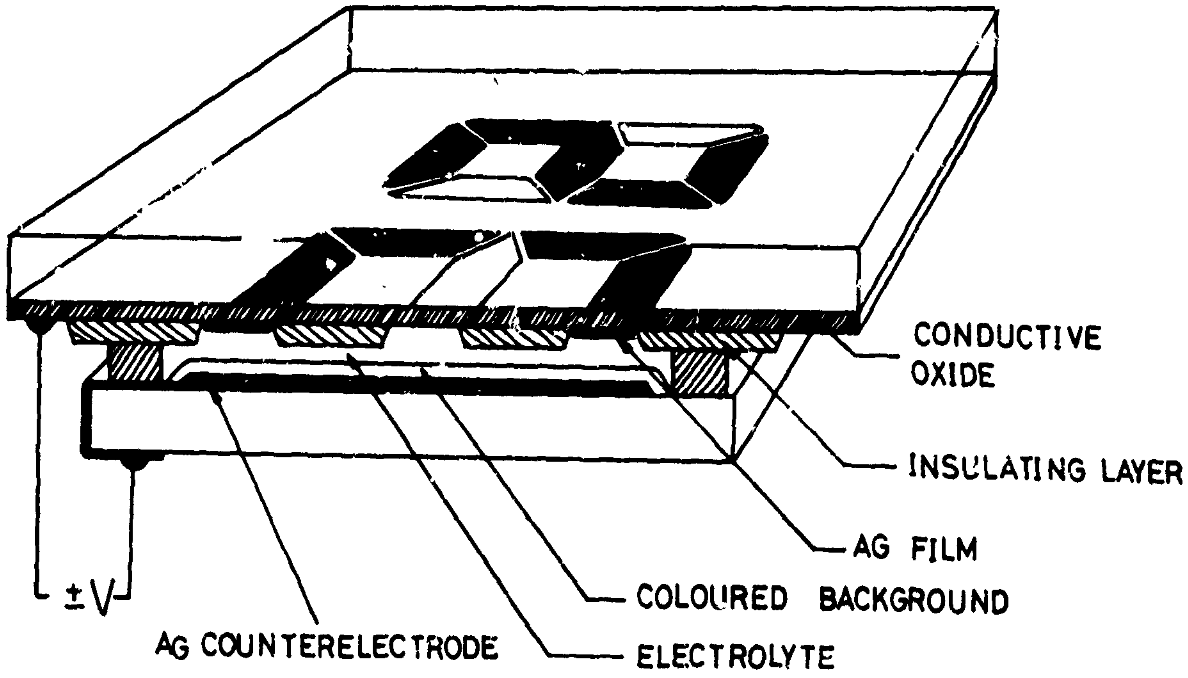

Fig.3.7.2 Scheme of an electrolytic display (after 3.7.9)

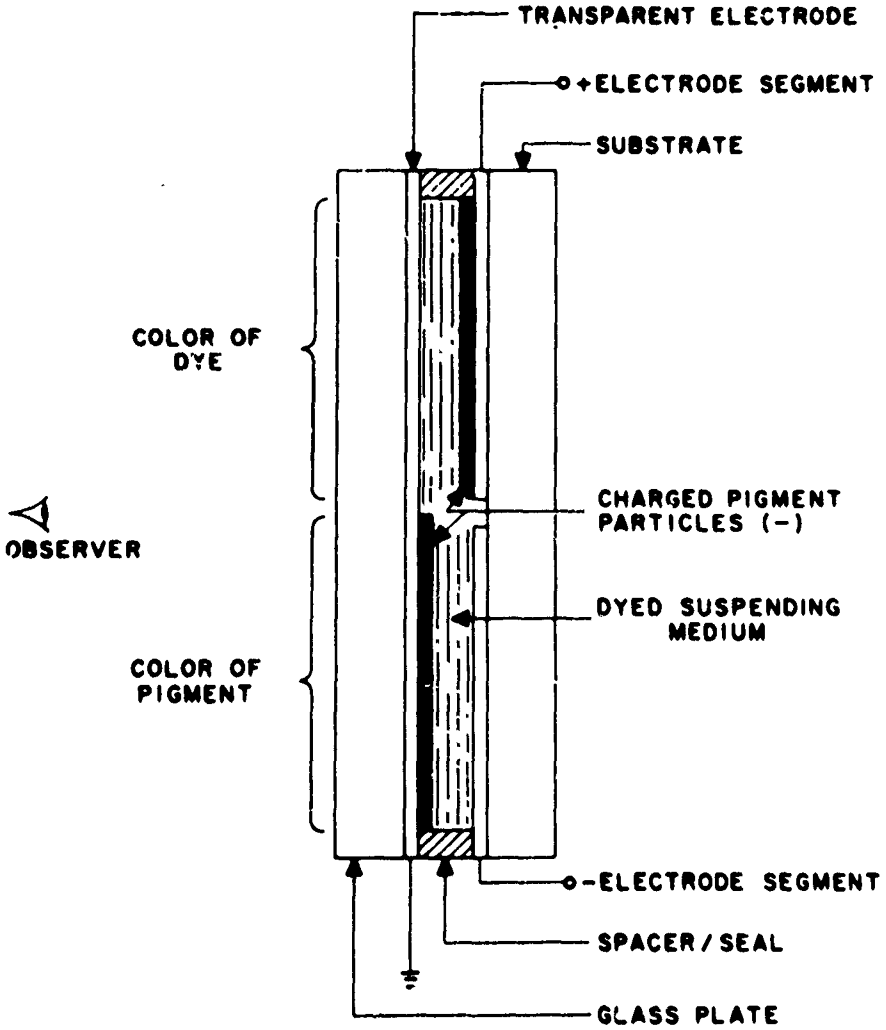

Fig.3.7.3 Typical structure of an electrophoretic display (after 3.7.10)

3.8 OTHER DISPLAY TECHNOLOGIES

3.8.1 FERROELECTRIC DISPLAYS WITH PLZT

3.8.1.1 Principles of operation.

The ferroelectric properties in certain ceramic materials such as PLZT (lead lanthanum zirconate titanate) can be utilized for display applications. PLZT is transparent in the visible light spectrum. Similar to liquid crystals, the PLZT ceramics have the property of scattering light or rotating the plane of polarized light under the influence of an electric field. The latter mode is due to a field induced birefringence (Pockels effect). When used as a display device the writing field is applied across the ceramic plate at the various image points by appropriate electrodes at the two surfaces (see Fig. 3.8.1). Once the information is written in, the state of the material remains (memory effect). To erase the information, an electric field can be applied by electrodes along two opposed edges or by a grid of interleaved electrodes on one surface (3.8.1).

The image can also be written in optically using a sandwich structure consisting of a photoconducting film and a ceramic plate (photoferroelectric imaging (3.8.2; 3.8.3). It has been shown that optical recording can be achieved in PLZT using the intrinsic photoferroelectric effect and thereby eliminating the requirement for photoconductive films (3.8.4; 3.8.5; 3.8.6).

Once the image has been stored it can be viewed by transmission or it can be projected onto a creen. In the birefringence mode, two polarizers are required.

3.8.1.2 State of development

Such devices have very short response times of 1-10 µsec per pixel and a resolution of up to 40 lines mm^{-1}. They represent a nonvolatile memory for the image with erase and rewrite capabilities. However, there are several disadvantages:
High voltage levels of 100 - 300 V are required, i.e. they are not IC compatible. In addition, the material exhibits a large capacitance and has a hysteresis characteristic so that all voltages must be approached from the same direction. Although much progress in the development of appropriate materials has been made and laboratory models of display devices have been demonstrated, such devices are not yet being considered for production. It is not apparent that they will have use in aircraft crew stations, and certainly not in the forseeable future.

3.8.2 FERROELECTRIC DISPLAYS WITH KDP

3.8.2.1 Principle of operation.

The ferroelectric effect in KDP (Pockels effect) is presently applied in a light valve (3.8.7). One realization is the TITUS valve which consists of an electron gun, similar to a CRT, wherein the screen is replaced by a target disc of monocrystalline deuterated potassium dihydrophosphate (KD_2PO_4), Fig. 3.8.2. The birefringence of this material can be varied by an electric field. The electron beam deposits on the surface of the target an electrical charge which is a mapping of the video image. The electric field associated with this charge changes the local polarization state of the crystal, so that linearly polarized incident light is reflected with a quadrature component which is modulated by the electric field. Intensity modulation of the reflected light is obtained by an analyser filter which suppresses the in-phase polarization component. The effect is strongest for high dielectric constants in the crystal, therefore it is advantageous to operate it near the Curie temperature (KD_2PO_4 : -50 °C) which is accomplished by Peltier elements within the tube.

3.8.2.2 State of development.

Systems with this tube operate with TV standard RGB signals, with frames of 503 - 1023 lines. It has the capability to retain the image (no flicker at refresh rate). Luminous outputs of 1500 lm have been obtained with an efficiency of 0.6 lm W^{-1}; large area contrast is 100% and the horizontal local resolution 900 pixels per line at 5% contrast. Systems are in production in limited quantities since 1982. The main field of application is large screen projection of computer generated or video images.

3.8.3 MAGNETO-OPTIC DISPLAYS

3.8.3.1 Principle of operation.

Magneto-optic displays are based on the Faraday-rotation of polarized light in magnetic domains (3.8.8; 3.8.9). The domains are created in small islands of magneto-optic iron garnet epitaxially grown on a substituted gadolinium-gallium garnet substrate (GGG). The typical size of an island is 100 x 100 μm^2, the thickness of the iron-garnet film is 5 µm. Each island stands for a picture element of the display component. Placed between polarizing foils, light is switched in transmission when changing the direction of magnetization due to the Faraday-rotation of the plane of polarization of polarized light (see Fig. 3.8.3).

To switch the direction of magnitization from one of the two stable states to the other, a heat pulse must be applied to the islands in the presence of a magnetic field of typically 10^{-2} Tesla. The thermal pulse is generated electrically by a current pulse applied to a thin-film resistance layer evaporated on the surface of each island. The magnetization switches into the direction of the applied field within a fraction of a µsec after a thermoelectric delay time of about 10-20 µsec.
Components with up to 64 x 64 picture elements have been realized on the basis of this technique (3.8.10). Due to electric crosstalk problems and increasing power of the addressing network, this x-y addressing scheme becomes more and more difficult with increasing number of picture elements. However, it is possible to use a decoupled x- and y-network for addressing (3.8.11) (see Fig. 3.8.4). This scheme is again based on x-y addressing, but only the y-addressing electrodes are used for thermal selection. All the resistance elements of a column of islands are connected in series. When applying a current pulse to such a column, all the elements of the column become simultaneously sensitive to a magnetic field at once. Then, the magnetic field required for switching is generated line by line via a thin-film net of x-conductors electrically isolated from the y-bars and arranged in the grooves between the islands. To achieve the different directions of magnetization, either positive or negative current pulses are applied.

3.8.3.2 State of development.

On the basis of this addressing technique, a display component with 256 x 64 picture elements has been realized with the picture elements arranged at a pitch of 120 µm (3.8.11). The width of the grooves between the islands (picture elements) of iron-garnet material is 25 µm. This determines the width of the metal conductors for the x- and y-addressing. These conductors are gold with a thickness of 5 µm. The x- and y-currents required to achieve switching are 1.5 A for the magnetic field generation and 0.35 A for the generation of thermal pulses. Both currents are applied for 10 µs using a drive voltage of 10-15 V. The overall average drive power to write information point by point at a speed of 1000 points sec^{-1}, for example, is 280 mW (2.8 W are required for 10 000 points sec^{-1} respectively). Since any switching state of the magnetization of an element remains stored, no drive power is necessary for holding of the information or for standby operation. Due to the storage capability, no flicker occurs.

The size of the display component is rather small. Therefore, it has to be installed in a projection system. The actual area of the above mentioned iron-garnet component with 256 x 64 pixels is 3 x 0.75 cm^2 and it is projected onto a screen with dimensions of 20 x 5 cm^2. A contrast of 20 : 1 has been achieved at normal room light conditions.

3.8.4 MAGNETIC PARTICLE DISPLAYS

3.8.4.1 Principle of operation.

The magnetic particle display is a flat-panel, matrix-addressable display device with memory. It forms images by arranging in a panel a large number of freely rotating spherical particles, each of which is a tiny permanent magnet, dark colored in one hemisphere and light in the other. Thus, the amount of ambient light reflected by the particle is a function of the particle orientation which is, in turn, controlled by a reversible magnetic field. This magnetic field comes from a nearby addressable magnetic array that functions as a memory. Sites in the memory are selectively magnetized by currents through conductors imbedded in the display. Schematic sketches of the magnetic particle and the construction of the magnetic particle display are shown in Fig. 3.8.5.

Matrix-addressing is possible in a manner comparable to the switching of computer memory cores by coincident pulses of currents. The memory is first magnetized uniformly in one direction. It is coercive and can resist demagnetization by reverse fields below a certain threshold. Only stronger fields can reverse the direction of the magnetization. Currents through the addressing conductors are designed to generate a reverse field below the threshold everywhere except at the selected site where the combined field-strength exceeds the threshold and the magnetization is locally reversed. The display will register a light spot against a dark background (or vice versa). Once the image is written into memory, it will remain there until changed by further addressing. The memory is non-volatile and sustains stationary images without consuming power (3.8.12).

3.8.4.2 State of development.

Magnetic particles have been made of polyethylene with powdered Strontium ferrite as a filler. They are naturally black; the light hemispheres are produced by applying a reflective metallic coating. Uniform spherical particles in sizes ranging between 20 µm and 400 µm have been made by generating droplets of the molten material (liquid polyethylene with the powdered ferrite in suspension) off the rim of a rapidly rotating toothed wheel and allowing them to solidify in-flight. These particles are then magnetized and metallized on one hemisphere while floating on a water surface (3.8.13).

Magnetic particle displays may be constructed with each particle encapsulated with a small amount of lubricant in its own transparent capsule, the capsules would then be cemented together to form the display panel. Encapsulation enhances the display's sensitivity by diminishing the interaction among the particles, and assures uniformity of the display by preventing migration of the particles (3.8.14).

Less sensitive displays were made by confining the free particles in thin (two-dimensional) cells of transparent materials. In some of these displays, the particles are surrounded by a transparent liquid lubricant, in others, the particles are dry. The displays without lubricants are genarally less sensitive (probably because they have more friction), have lower contrast (because the blacks are not as black), but are more pleasing to look at; and potentially usable over a wider temperature range (since they contain no liquid to boil or freeze). These displays were observed to generate clear images with wide viewing angles and contrasts of up to 15; images do not "wash-out" even under high levels of ambient illumination.

The addressing matrix (cross-grid of electrical conductors) and memory are fabricated as an integrated unit. Addressing matrices of high resolution (as high as 30 lines cm^{-1}) were made by photoetching copper coatings on two sides of a Kapton (polyimide) foil - the grid in the x-direction is etched on one side, and the grid in the y-direction is etched on the other side. The Kapton is then etched away everywhere except where it is protected by the copper grids. The holes created by etching away the Kapton are then filled with ferrite powder which serves as the display's memory. The ferrite powder in the display's memory is different from the material of the magnetic particles. In the particles, highly coercive Strontium ferrites are used. For the memory, relatively low coercive square-looped Lithium-Nickel ferrites are chosen to minimize currents needed to switch the display elements.

The electric write currents for displays using the presently available magnetic particles with 10^{-3} Tesla sensitivity and Lithium-Nickel ferrite memory material, is about 1 amp per 100 μm of pixel size. These currents are typically applied as short pulses, of duration 1 μs. Once the image has been written, the display's non-volatile memory will sustain the image, then the electric drive power may be turned off.

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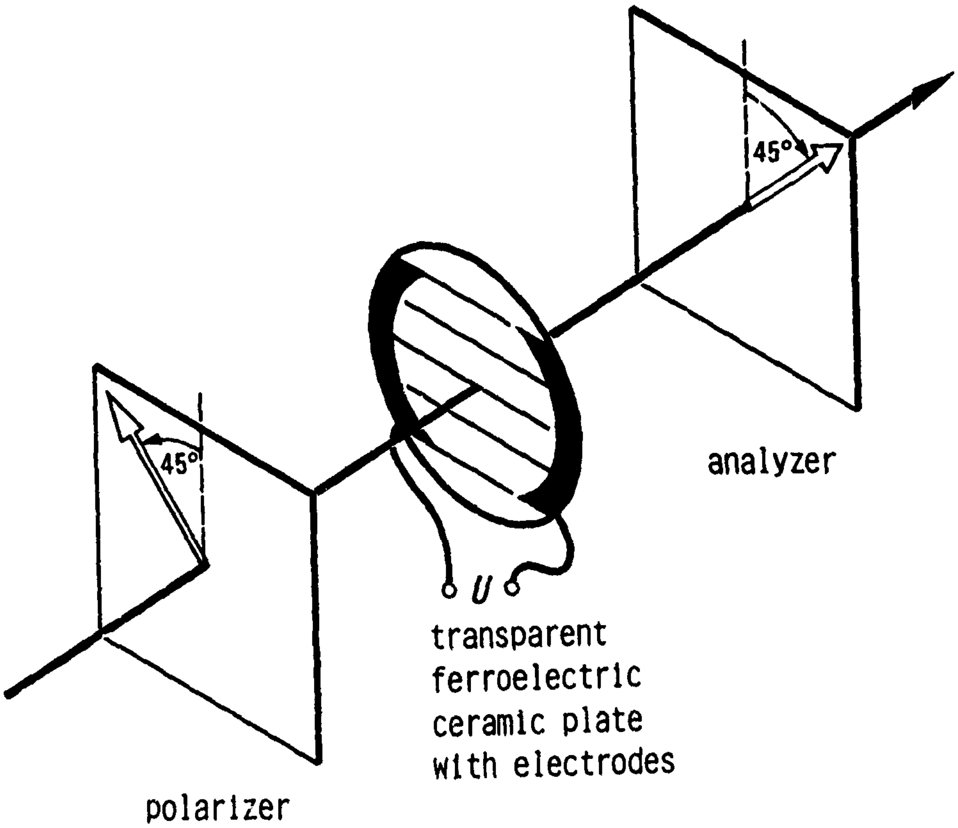

Fig.3.8.1 Principle of operation of a ferroelectric display

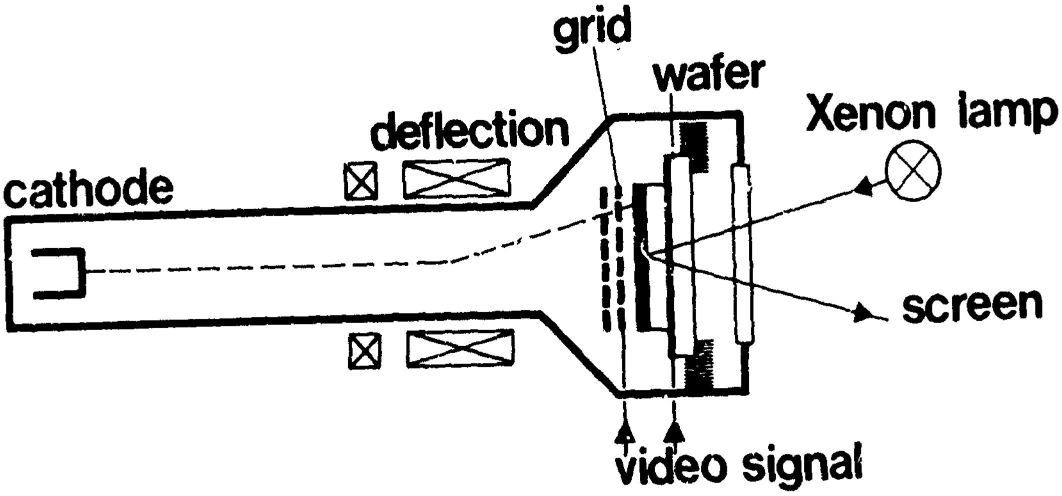

Fig.3.8.2 Cross-sectional view of the TITUS light valve

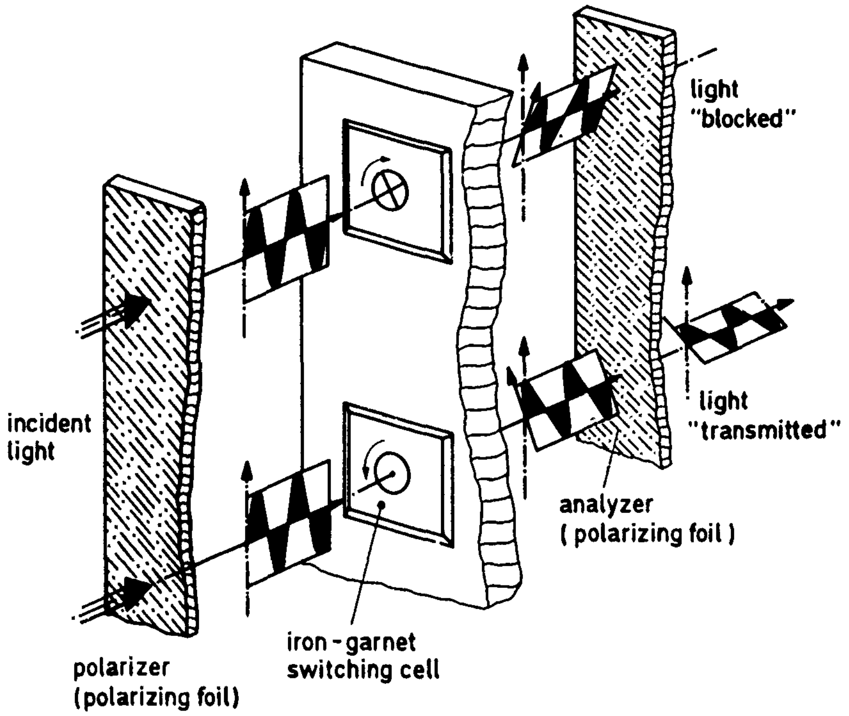

Fig.3.8.3 Principle of operation of a magneto-optic light modulation element

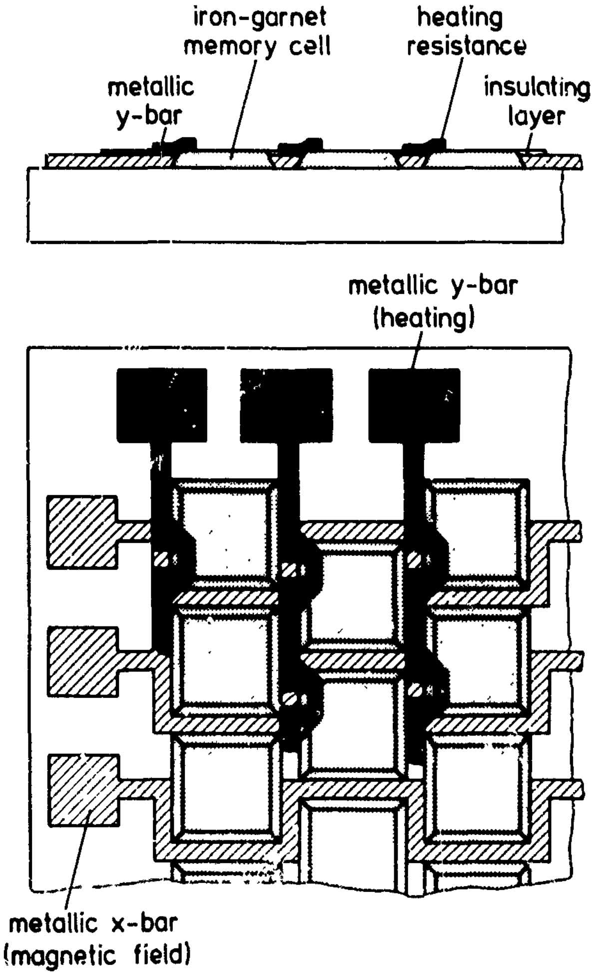

Fig.3.8.4 X-Y-addressed iron-garnet display with X-bars (meander-shaped conductors) for magnetic field selection and resistances for thermal Y-selection (after 3.8.11)

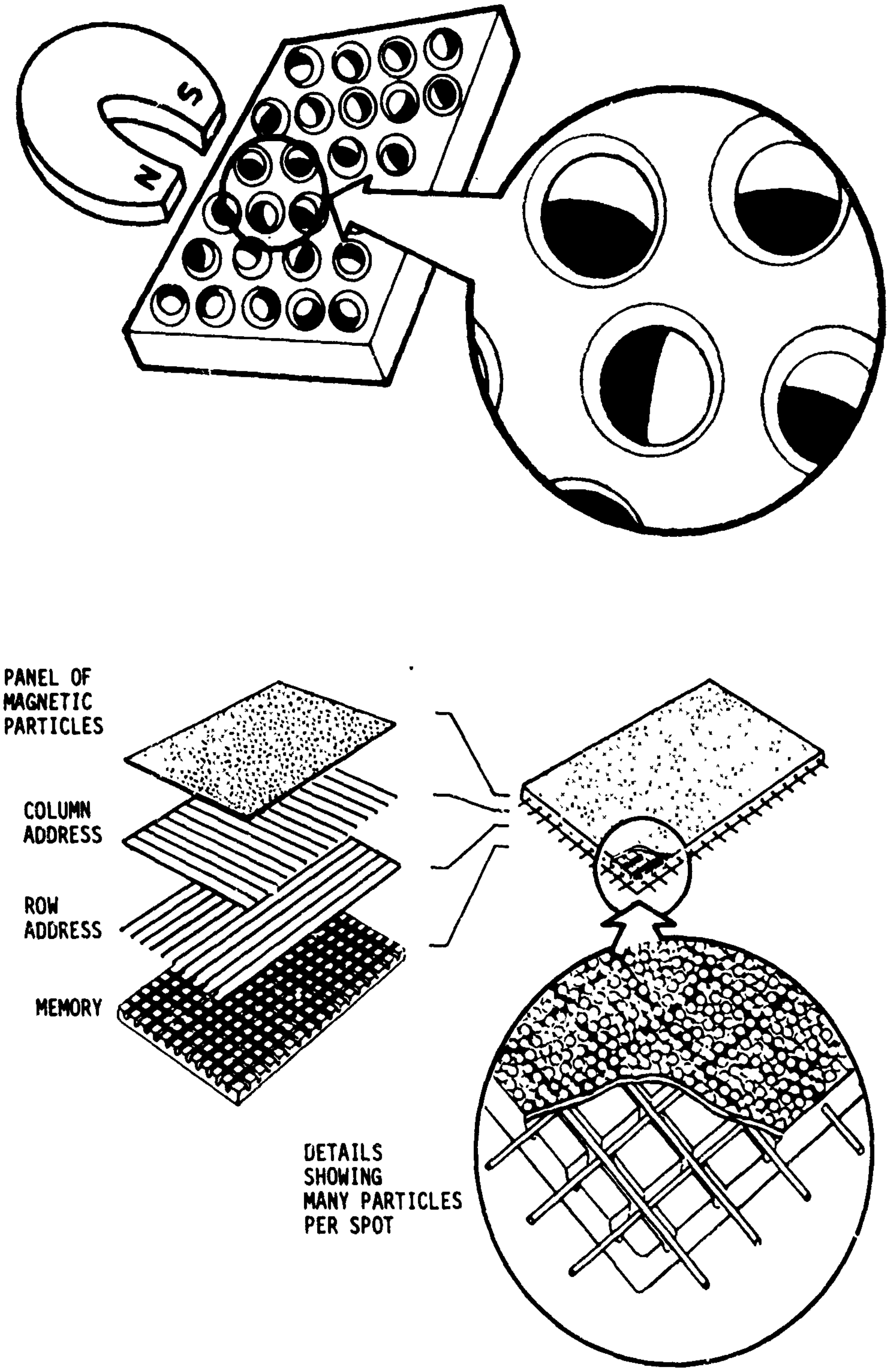

Fig.3.8.5 Schematic sketch of the principle of operation (upper part) and the construction (lower part) of a magnetic particle display (after 3.8.13)

CHAPTER 4, APPLICATIONS

4.1 CLASSIFICATIONS

The applications of electronic display technology in military aircraft can be divided into four basic classifications of visualization format. These formats and their definitions are taken from the 1979 Tri Service Airborne Flat Panel Display Technology Report (4.1). The classifications are listed in order of decreasing complexity as measured by the expected maximum number of picture elements (pixels) they might contain. Although not a perfect guide, the engineering problems of drive and interface design, fabrication, connection, and packaging all increase sharply with the number of picture elements.

4.1.1 VIDEO

Video devices are those characterized by today's raster television where high-data-rate (at least 25 times a second) information is presented in a pictorial form with multiple shades of grey. This would be utilized for display of sensor information such as forward looking infrared (FLIR), low light level television (LLLTV), and scan-converted radar. Presently used raster formats of 525, 625, 875, and 1024 lines are considered typical.

4.1.2 VECTOR-GRAPHIC

Vector-graphic devices are those which present information in both alphanumeric and simple line drawings with typically one or two levels of luminance in addition to the off state. These devices would be utilized for alphanumeric and graphic information from the aircraft, avionic, engine, and ordnance subsystems.

4.1.3 MESSAGE

Message devices are those which present alphanumeric information at low-data rates with not more than two levels in addition to the off state. These would be used for caution or warning indicators as well as for general command and control applications. Typical requirements indicate message formats of approximately 20 characters by 15 rows in which each alphanumeric is arranged in a 5 x 7 or 7 x 9 dot matrix configuration.

4.1.4 DISCRETE

Discrete data devices are those which present small amounts of alphanumeric or simple graphic information. These devices could be used for small readouts, legends, paragraphs and multifunction key legends.

Specific applications of interest use one or more of the display formats as shown in the following matrix.

	Visualization		Formats	
	Video	Vector-graphic	Message	Discrete
APPLICATION				
HEAD-UP DISPLAYS	X	X		
HEAD-DOWN DISPLAYS	X	X		
HELMET-MOUNTED SYSTEMS	X	X		
MISSION MANAGEMENT DISPLAYS		X	X	
KEYBOARD DISPLAYS			X	X
ALPHANUMERIC MODULES			X	X
MAXIMUM NUMBER OF PICTURE ELEMENTS	10^6	10^5	10^4	10^3

4.2 HEAD-UP DISPLAYS (HUD)

The HUD is a collimated (focused at infinity), optically projected display designed specifically for airborne use. The HUD combining glass is located between the aircraft windscreen and glare shield and transmits the real-world scene directly while reflecting the display image so that the two superimposed images are viewed simultaneously the pilot. The optical magnification of the HUD is scaled one to one for symbols which need to match the real world scene. Indications such as pitch angle may be greater than one to one. Because the reflected image is collimated, the angular size and position of symbol cues projected within the display field-of-view remain constant with pilot head motion. The HUD is used to project vector-graphic and video information. The primary functions of the HUD are flight guidance and weapon aiming, therefore a high quality optical system is required that can maintain accurate symbol positioning. The HUD is also used to display symbol cues for other mission modes such as take-off, landing, navigation, terrain following and ground collision avoidance. Electro-optical sensor displays such as Forward Looking Infrared (FLIR) can also be presented on the HUD. Figure 4.1 shows a functional diagram of HUD optics.

The combiner is located between the aircraft windscreen and glare shield with sufficient clearance to minimize secondary reflections from the windscreen. The HUD must clear the pilot's ejection line, usually with a camera mounted in front of the combiner. The HUD can extend beyond the surface of the instrument panel, but it must not obscure the pilot's line-of-sight (LOS) to other surrounding displays and controls or the pilot's "over-the-nose" LOS. These geometric constraints determine the specific optical performance that can be obtained in any particular aircraft installation.

A total field of view from 20 to 40 degrees is desirable for fixed wing aircraft. A nominal contrast ratio of 1.2 against a 10^5 lux (10^4 fc) background is required for graphics. Symbol position accuracy of one milliradian over the central 5 degrees of the field-of-view is required. A three times larger resolution per picture element is required throughout the field of view. Almost all HUD's have been based on CRT technology, however, see section 3.3.7.3 for discussion of a different HUD projection system.

Recent advances in holographically formed optical elements enable the construction of combiner elements which have very high (90%) reflectivity over a very narrow band of optical wavelengths. This enables a bright display to be generated while imposing very little attenuation of the outside scene. Narrowband CRT phosphors are available to which the spectral response of the holographic plates are matched. In addition to the above advantages the angular selectivity of the holographic elements enable compact optical units to be constructed with wide fields of view. Most existing military HUD's are monochromatic. While several hues of color may be desirable color is unlikely if holographics become fashionable. Reference (4.2) provides an in-depth literature review of 293 publications relating to the HUD for aircraft cockpit application.

4.3 HEAD-DOWN DISPLAYS (HDD)

Head-Down Displays are direct view, flexible information format displays having the capability to display both graphic and video information. The Horizontal Situation Display (HSD) and the Vertical Situation Display (VSD) are two classes of HDD that are associated with two specific types of flight information. Reference (4.3) discusses the use of map displays in high performance aircraft. Reference (4.4) discusses HDD in military transport aircraft.

The HSD is a flexible information format (i.e., multifunction) display that, at a minimum, displays the heading information portrayed on a conventional electromechanical Horizontal Situation Indicator (HSI). In essence, it has a designated information function, that being the display of information giving aircraft orientation and any related situation information with respect to a position in a plane parallel to the earth's surface. In addition to the heading indication, bearing pointers, distance, and course deviation indications provided by an HSI, the HSD should be able to provide combinations of:

- Aeronautical charts and/or Electronically Generated Maps
- Navigation, Target/Drop Zone Identification
- Electro-Optical and Radar Sensor Video
- Flight Control Cues
- Electronic Warfare Information

The VSD is a flexible information format (i.e., multifunction) display which, as a minimum, displays the attitude information portrayed on an electromechanical Attitude Director Indicator (ADI). The VSD can provide information similar to the HSD but with respect to a plane that is perpendicular to the earth's surface. The orientation of an HUD and HDD in the cockpit are shown in Fig. 4.2. In the illustration the HDD shows an HSD information format while the HUD shows ADI information.

The sensor-video imagery of target detection and identification tasks associated with search and rescue, reconnaisance, and weapon delivery are the controlling factors that determine resolution requirements. (See Sect. 2.2). There are also practical limits on site mandated by the limited space available. Current displays have dimensions of about 13 x 13 cm maximum.

The requirement for both the number of grey shades and the luminance ratio between adjacent shades on a video display are the subjects of considerable controversy. The reported number of grey shades needed as a minimum to fully satisfy viewer visual requirements varies from five to thirty for fixed daylight viewing conditions, with the luminance ratio which defines a gray shade varying from 1.4 to 2. To the extent practical the number of grey shades in the display should be matched to the number of grey shades in the sensor.

Sensor-video information can be satisfactorily displayed at 4-5 pixels/mm. on a nominal 525 line display. Display sizes are typically in the range 50 mm diagonal to 300 mm diagonal. The main constraint which forces CRT displays to be small is the limited space in the cockpit. Of less significance is the requirement to provide sufficient luminance to remain legible. (See Sect. 3.1). It is desirable to maximize the ratio of display active area to the total panel area occupied, subject to the constraints imposed by clutter and the need for light sensors, controls and switches. Conversely, minimum separations between functionally different types of display information and the need for instrument panel structural integrity both suggest limiting the proximity of adjacent displays. Nominally, 10% of the active area linear dimension of the larger of two viewed displays is needed to separate different but related task information. Larger distances are needed to separate information for unrelated tasks.

4.4 HELMET MOUNTED SYSTEMS

Helmet Mounted Systems have been used for over ten years but until recently have not been generally accepted. Helmet Mounted Systems are discussed in References (4.5)-(4.8). Examples are shown in Fig. 4.3 & 4.4.

These systems fall into two related categories: sights and displays. A Helmet Mounted Sight (HMS) is designed to measure the pilot's line of sight to a target in relation to the airframe and to process that information for use in direct control of weapon delivery systems and remote sensors. The Helmet Mounted Display (HMD) provides the crew member with a head-up TV display monitor which is lightweight, low-powered, gives high resolution and can also be used as a sight. In either case the attitude of the helmet must be measured relative to a selected reference frame.

There are, in general use, three systems which are used to measure helmet angle and position. One is optical, one uses infrared and the other is magnetic in operation. For the helmet to operate as a sight it is necessary to have an aiming mark. The simplest possible sight is an illuminated cross or circle whose image is focused at infinity.

The image source can be a graticule illuminated by a miniature lamp or a matrix array of any suitable technology. This image is then projected and collimated by the optics and presented to the eye after reflection from the visor. Latest advances include the use of a diffractive optical element in the visor which both reflects and collimates the image.

Another version removes weight and heat dissipation problems by forming the image remotely and conveying it via a fiber-optic pipe to the combiner. The piping avoids high voltage going to the helmet, however, there has been some difficulty with the flexibility of the fiber-optic pipe.

An advantage in using a matrix display is the flexibility to change the image. In addition to the aiming mark, discrete data such as speed, range, altitude and pressure can be digitally displayed. Also, flashing direction indicators can direct the crew member where to look for a target.

The Helmet Mounted Sight allows the pilot to acquire the line-of-sight to a target outside the normal field-of-view of the Head-up Display. This data is then immediately available for use by the Weapon Aiming System or to update the Navigation system by spotting waypoints.

In addition, both slewable weapons and sensors can be slaved to the helmet. The pilot's head, in effect, becomes a very sophisticated and ergonomically attractive direction controller, thereby integrating the pilot's visual/monitor skills with the specialized accuracies of weapon and navigation systems.

The Helmet Mounted Display (HMD) as opposed to just a sight, combines a Helmet Angle and Position Sensing System with a helmet mounted high resolution display and optics (presently a CRT, Section 3.1) to provide a highly flexible system incorporating many of the facilities to be found in both head-up and head-down displays. Because it is a quality imaging system, it is possible to present both pictorial and symbolic information together offering a combination of synthetic imaging and sighting information.

The recent developments concerned with miniature cathode-ray tubes has ensured that in spite of their size (19 mm dia.) there is no reduction in performance from these devices. Also by mounting a miniature CRT on the helmet close to the eye this effectively provides the equivalent of a much larger panel-mounted CRT with the advantage in saving both weight and power in the process.

Under good viewing conditions the eye can resolve 0.25 milliradian and it is quite obvious that the performance from the display will fall short of this. It is, however, very important to get the maximum benefit from the HMD by having high resolution for the picture.

Another very important factor associated with Helmet Mounted Displays is that the picture scale and viewing angle should not be compromised by limitations in the optics. The first factor to be realized is that the image to be displayed will be collimated to appear at infinity since it should register with the outside world. Secondly, the instantaneous viewing angle should preferably be 40 degrees in azimuth and 30 degrees in elevation (See Section 2.2) with an exit pupil of 2.5 cm to accommodate a range of users.

When one bears in mind that the objective of such a design must be to achieve the above specification with the least weight penalty and with minimal obstruction to direct vision, some idea of the problem emerges. The best solution appears to lie in the use of a diffractive optical element preferably embodied in the visor which will both focus the image at infinity and operate as a high efficiency (90%) reflector at the narrow band wavelength of the CRT phosphor but offering see-through ability at all other visible wavelengths. Color switching is a possible option. It is appropriate to discuss mechanical aspects here before leaving the optics. The first concerns the weight of the CRT package and optics on one side of the helmet. This should be counterbalanced by a similar weight on the opposite side. The second is adjustment of the optics to compensate for different users. Such an adjustment to ensure that the center-line of the optics is aligned with the user's eye-ball may reduce the exit pupil size with corresponding reduction in the size of the diffractive optic. Also an interesting solution might be to mount the CRT off the helmet and transfer the image via a fiber-optics pipe to the helmet. This also removes high voltage from the helmet. At present, however, suitable light pipes degrade the picture and at the same time impose undue constraint on the helmet.

There could be considerable advantages in providing images to both eyes. This would combat the inevitable binocular rivalry which will otherwise occur and would ensure harmonized viewing by both eyes. However high vibration can cause convergence problems and flicker detection may be increased with biocular viewing (Ref. 4.12).

The principal advantage of the Helmet Mounted Display lies in the fact that data is presented to the eye irrespective of the direction of regard. This is particularly important when operating at high speed close to the ground. The data can be conveyed subjectively to the eye while the pilot's concentration is focused on flying. Also in the surveillance operational role both during the day in poor visibility, and at night, the ability to slew sensors directly so that the sensor is oriented to the viewing direction of the pilot, provides a "head out of the cockpit" capability.

4.5 MISSION MANAGEMENT DISPLAYS (MMD)

The first three display applications (HUD, HDD, HMD) are used to display information used by the pilot for primary flight control. The displays appear centrally located relative to the pilot's visual scan so as to attract his primary attention. Mission management displays are more likely to be positioned to one side than to be centrally located with respect to the pilot (see Fig. 4.2). They include map displays, aircraft situation data, and aircraft subsystems data such as engine, fuel, hydraulic, oxygen, ordnance, navigation, communications, countermeasures, etc. One example is a flexible information format to display computer generated vector graphic aircraft situation data. Another example is an optically combined display of tactical data overlaid on the microfilm image of an aeronautical chart.

The first example is a graphic display that has no requirements for video presentations. A two- to three-shade of grey display can take advantage of sizes from 10 cm x 10 cm for the display of the more conventional flight control data up to 30 cm x 30 cm for the display of terrain contours, contact analog situation data, symbolic map data such as threats, weapon engagement perimeters, computer synthesized targets, computed optimal flight paths, and navigation displays. For a scanned matrix display a minimum resolution of 2.5 pixels/mm and up to 250 Hz refresh rate for the display of vector-graphic display imagery is necessary. The requirement is based on the minimum requirements to provide both the appearance of smooth continuous image motion and simultaneously the precise scales, pointer positioning, vector rotation, and vector translation positioning accuracies needed for the rapid, accurate presentation of vertical and horizontal scale, bargraph, round dial, graphical, symbolic map, and perspective information formats. This pixel density also allows the presentation of upright numerics and alphanumerics in highly legible and identifiably 10 x 14 dual stroke width or larger fonts. Small, visually complex characters, i.e., alphanumerics, to be rotated, must have stroke widths that contain a minimum of three pixels and simultaneously satisfy the 15 per cent of character height requirement of good legibility (e.g., 15 x 21 array font size or greater independent of display element density). (See Section 2.1)

Presently being used are monochrome CRTs utilizing two discrete luminance levels in addition to off. Current sizes are approximatley 12 cm x 18 cm, oriented as a normal page of a book. This size is a compromise between that requested by human factors studies and limitations based on airframe installation requirements. Present studies of systems utilizing CRTs indicate that an alpha-numeric character must be at least 5.5 mm high, with an ideal height being 6.5 mm (assuming a 70 cm viewing distance.) The graphics capability should include simple graphs, geometric shapes and lines generated by a display with uniformly spaced horizontal and vertical picture elements. Color is desirable to accentuate information.

Certain applications may favor the display of actual aeronautical charts which have resulted from a long interplay between cartographers and users (4.3). Although they are not always ideal for display purposes, charts from this mainstream of development are likely to form the basis of future displays. Their optimum display demands high resolution, full color for the projected map although the overwritten data can be monochrome.

An optically combined display provides high resolution color as well as being compatible with a full electronic display suite. It provides a form of dual redundancy and installs in a single unit. An alternative using the same data base is the remotely scanned map, which depends on the availability of a full color high resolution display embodying a proper solution to the problems of high ambient light.

The all digital solution is a possibility which awaits a viable solution of the editorial and logistic problems of a digital data base together with a proper full color display head. There are considerable digital hardware and software problems and the storage required could be massive, even in terms of devices such as bubble memories. Bearing in mind the complexity of cartography as an activity and the long history which has led to present mapping material, it would be a considerable task to demonstrate that such a system is operationally superior to a combined display. It is possible to filter information with an all digital data base, e.g. show SAM sites or all radar sites on demand.

4.6 KEYBOARD DISPLAYS

Keyboard displays afford the possibility of combining separate symbols into one functional command, thereby integrating the control of several sets of functions presently provided by separate dedicated control panels and the management of several primary multifunction displays. They can reduce operator real-time workload both by allowing preselection of flight tasks on a functional or mission segment basis and by providing flexible but orderly procedures in the conduct of the total crew station management. Through the incorporation of programmable switches and information processing, the plethora of dedicated control switches can be sharply reduced.

It is typical to have a legend area for each switch which consists of two rows of four to eight characters per row. The individual legend should use as a minimum a five by seven matrix (2.1), although a seven by nine matrix is preferred. Examples of each font are shown in Fig. 4.5 and 4.6. Experiments have established (4.9),(4.10),(4.11) that a 5 x 7 matrix is the minimum required while matrices larger than 7 x 9 do not lead to meaningful improvements. Character generators using 5 x 7 and 7 x 9 are the ones most readily available. Fifteen to thirty switches are desirable. The legends should be viewable under bright sunlight at a minimum contrast ratio of 1.2 and for some applications be usable with night vision goggles.

4.7 ALPHANUMERIC MODULES

Modular readout devices, specifically alphanumerics and bargraphs, are needed to provide legible, reliable, variable-format control display components. Readouts will be needed both in discrete and mosaic formats to allow variable fonts and positioning in alphanumeric modes and/or line positioning for bargraph applications. Discrete readouts take the form of individual or grouped alphanumerics. They are used in applications which range from one or two digit displays and legend lamps, to message displays of several rows of up to 20 or more characters per row. Reference 4.13 discusses these applications in more detail.

These devices can be developed as modules employing three basic forms:

- Segmented numerics
- Dot-matrix alphanumerics
- Small area mosaics

It is desirable that these modules should be constructed so they can be abutted on all four sides and incorporate all necessary drive and address circuitry. This concept will allow a wide variety of form factors and display areas which are appropriate for application of these devices. Applications include: control panel numeric and alphanumeric readouts; flight, mode, and caution legend lamps; and multi-legend display switches. The devices need to be readable in bright sunlight as well as with night-vision goggles. The resolution should be from one to six pixels per millimeter.

4.8 SUMMARY

In this chapter the applications of electronic display technology were divided into four classifications of visual format based primarily on the maximum number of pixels required. Six specific applications were described and each was considered to span two of the visualization formats. In the next chapter an assessment will be made of the potential of each modern display technology to meet the requirements of the twelve applications areas identified here.

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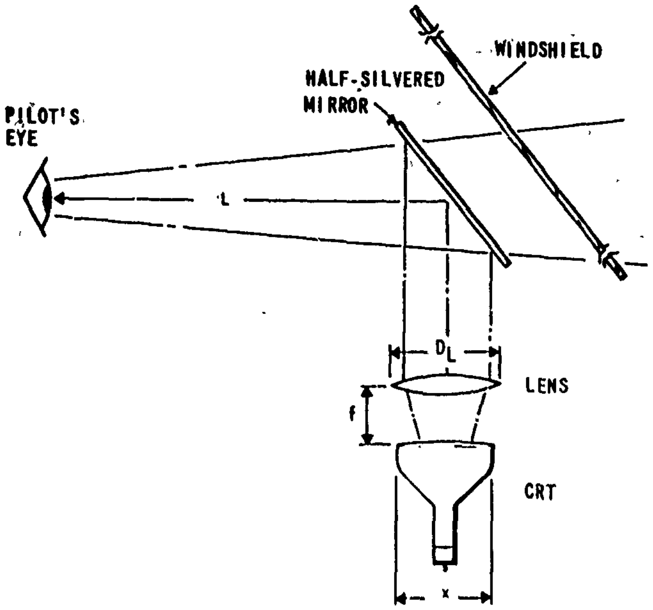


Fig. 4.1. Heads Up Display (HUD) Optics

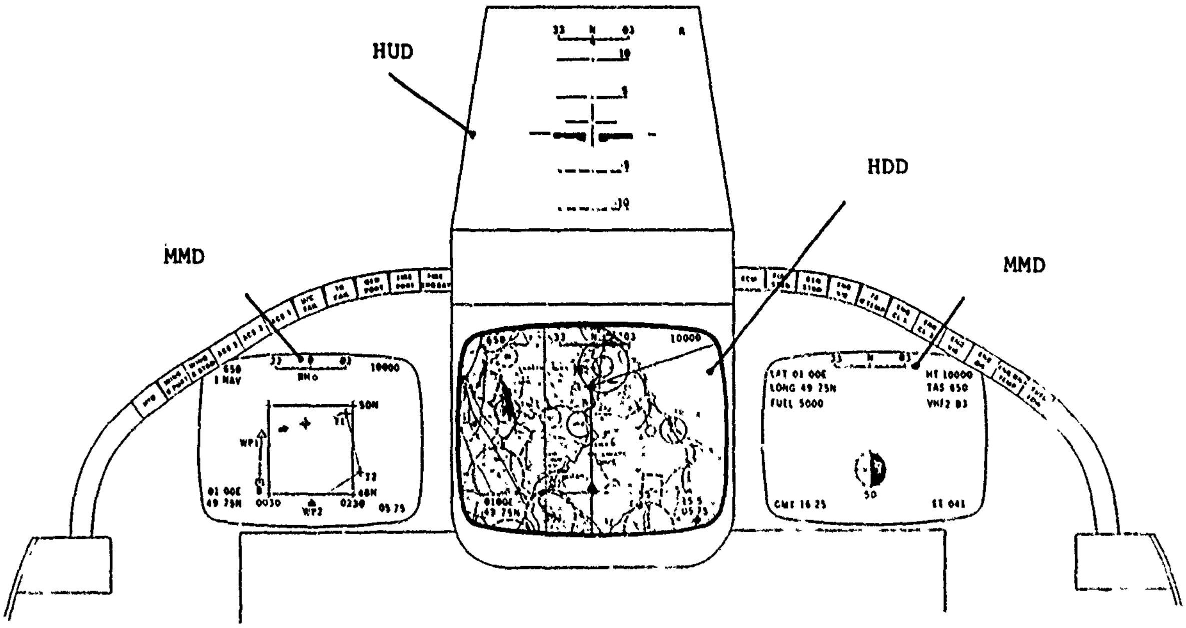
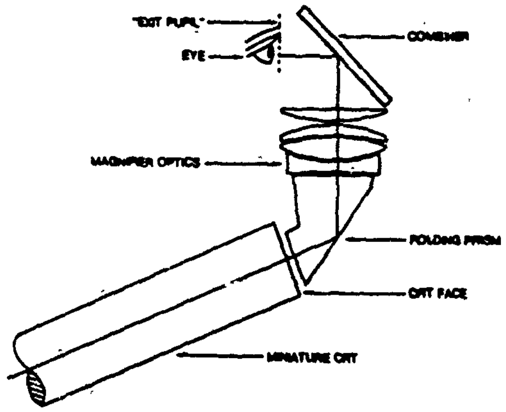


Fig. 4.2. Cockpit Orientation of Displays



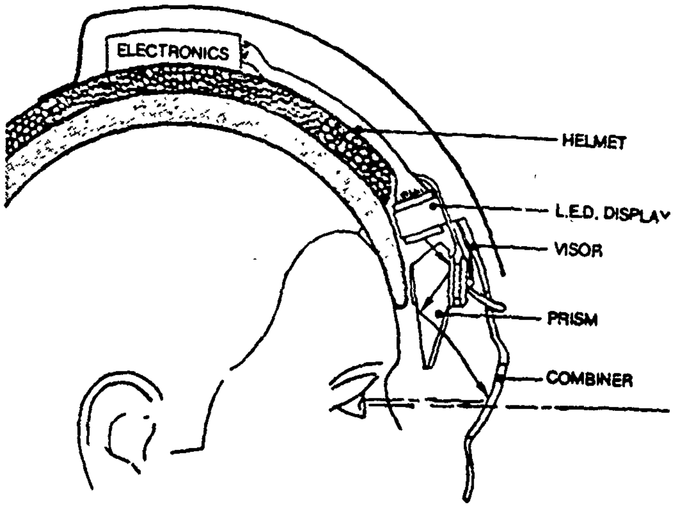
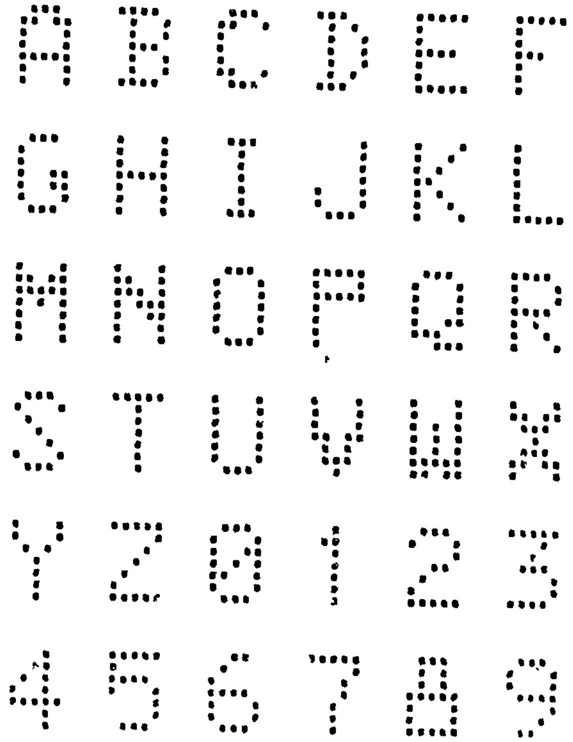


Fig. 4.3. Simple magnifier HMD with flat combiner; Hughes Aircraft Co. Ref (4.6)

Fig. 4.4. Simple magnifier HMD using LED image source and spherical combiner; Marconi Aviation. Ref. (4.7)



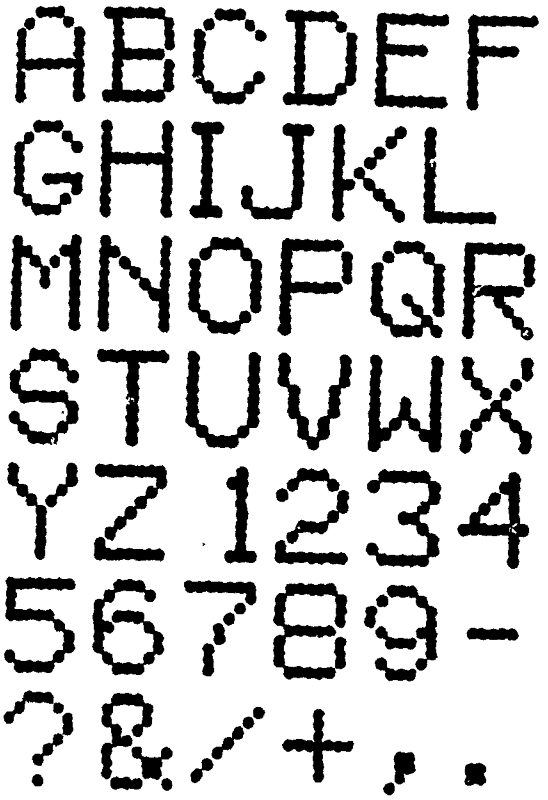


Fig. 4.5. Modified Huddleston Font 5 x 7 Dot Matrix. Ref. (4.11)

Fig. 4.6. Sherr 7 x 9 Dot Matrix Font. Ref. (4.9)

CHAPTER 5, MODERN DISPLAY TECHNOLOGY ASSESSMENT

In this chapter relative comparisons are made among the display technologies described in Chapter Three. Performance measures which have been introduced previously are summarized. A matrix of performance measure against technology is generated. Advantages and disadvantages not already evident from the matrix are listed. The relative importance of the performance measures are discussed in connection with the applications described in Chapter Four. Finally an assessment of the potential of each technology for each application is summarized in a single table.

5.1 MEASURES OF PERFORMANCE

The parameters selected for a performance comparison of the display technologies are summarized below. It is clear that the value of many performance parameters depend upon the particular conditions under which the technology has been applied. In order to make a fair comparison it is assumed that in all cases where such standardization is appropriate the application in mind is a 14 cm diagonal, direct-view display of 480 x 640 pixels. Since this specification essentially fixes the resolution it will not apply to the two parameters which measure resolution capability. This video application is fairly high up on the cost-complexity curve. By contrast, an alpha-numeric application would not offer as much challenge to an individual technology, and therefore would not highlight the performance comparisons as well. For less demanding applications there are a different set of trade-offs, and some of the data presented assuming the video application may not be appropriate.

5.1.1 Maximum Luminance

Luminance is defined in 2.1.1 as the emitted luminous intensity per unit area in candelas per square meter. The maximum luminance is the largest value of luminance expected from the technology when applied to the standard application defined above based upon what is known about the present state of the art within the technology. The definition applies only to active displays which emit their own light. The maximum luminance is important because it indicates how bright the display can be.

5.1.2 Maximum Reflectance Ratio

For passive displays the emitted luminous intensity is proportional to the incident luminous intensity. The ratio of the former to the latter is defined as the reflectance ratio. The maximum reflectance ratio is the largest value expected from the technology when applied to the standard application defined above. It applies only to passive displays.

5.1.3 Contrast

As discussed in 2.1.2 contrast is a controversial notion. We refer here to C_v, the ratio of the display foreground luminance less background, $L_f - L_b$, to the background luminance of the perceived display area, L_b.

$$C_v = \frac{L_f - L_b}{L_b}$$

The ambient lighting is specified at a level of 10^5 lux and the display is assumed to have 640 pixels per picture width. The tabulated value is the best expected, possibly with a contrast enhancing filter, for the technology under the specified conditions. It is important because of its influence on viewing performance. Passive displays may still require cockpit illumination due to veiling luminance. A passive display cannot be read without extra illumination when bright external light comes from in front of the aircraft even though it can be seen readily when bright external light comes from behind.

5.1.4 Efficiency

Efficiency is defined as the ratio of the luminous power output to the total electrical power input in units of lumens per watt. The total electrical power input includes the power dissipated in the drive electronics. High efficiency is desirable to limit heat dissipation. The definition is not applicable to passive devices.

5.1.5 Dimming Ratio

The dimming ratio is defined as the maximum luminance obtainable divided by the minimum luminance obtainable in a display device without extinguishing pixels. The definition is not applicable to a passive display. Dimming ratio is important in applications where the same device must be used in high ambient conditions such as sunlight as well as low ambient conditions such as during night operations.

5.1.6 Typical Resolution

Resolution is defined as the number of pixels per linear dimension. The adjective, typical, implies the maximum value that is associated with applications in each technology (the standard application described above does not apply to this parameter). The purpose of this performance measure is to indicate relative resolution capability as a function of technology.

5.1.7 Maximum Number of Pixels Per Picture Height

The purpose of this parameter is to indicate resolution capability in terms of picture height as opposed to linear dimension. In some technologies resolution is limited by pixel size. In other technologies the limitation is on the maximum number of pixels. As above, the standard application does not apply and the purpose of the performance measure is to indicate relative resolution capability.

5.1.8 Gray Scales

The number of shades of light available in going from dark to bright measured by luminance gradations that differ by the square root of two. The number of gray scales is important because of its influence on visual perception and discrimination. For many applications of interest it is desirable to match the number of gray scales of the display to the number of quantization levels of the sensor.

5.1.9 Viewing Angle

The viewing angle is defined as the maximum angle in degrees at which the display can be viewed measured relative to the normal to the display face. For the LCD technology the maximum viewing angle can vary from 10 to 80 degrees depending upon how the technology is applied. (See sections 3.3.2.7, 3.3.5, 3.3.6.4.)

5.1.10 Current Color Capability

Current color capability refers to the ability of the technology to display simultaneously one, two or three primary colors, considering only present state-of-the art and excluding future potential. The importance of color is discussed in 2.4.1.

5.1.11 Storage Temperature Range

This is the temperature range over which the device can survive during storage. Three ranges are selected to correspond with typical military specifications.

5.1.12 Uncompensated Operating Temperature Range

This is the temperature range over which the device can carry out its desired function without degradation in performance.

5.1.13 Current System Cost (per pixel)

The purpose of this parameter is to indicate current relative cost of the individual technologies. Although cost is an extremely important parameter it is very difficult to specify quantitatively. Consequently, a relative scale is used for comparative purposes and is based on professional judgment.

5.1.14 Projected Cost (per pixel)

Because most of the display technologies are developing rapidly there is great potential for future reduction in the cost per pixel. This is indicated again by using a relative scale for comparative purposes and is based on professional judgment. The cost is for the system and includes the drive electronics.

5.1.15 Operating Life

Operating life is defined as the mean time to failure of operational displays measured in hours. It is specified in one of two ranges.

5.2 CAPABILITY OF TECHNOLOGY

A value for each measure of performance is tabulated in Table 5.1 for each display technology. The reader is cautioned that he must exercise care in the use of the table for a number of reasons. Firstly, in many cases there is a large uncertainty in the numerical values of the entry. Secondly, it is important to specify the conditions under which the numerical values apply. Many of these conditions have been specified in Section 5.1. However, not all of the conditions can be stated when trying to generalize over a technology that includes a large number of different individual devices. Thirdly, the technical area under consideration is growing rapidly and the information presented can become obsolete over a very short time interval. Finally, the data represent inputs from a number of qualified experts who exhibited strong differences of opinion on several crucial parameters. In some cases the data are based on an average or a majority vote which was reached only after heated debate. It is ironic that performance information which is the primary interest of the user is at the same time the most difficult information upon which to obtain a consensus from the experts. It must also be emphasized that the different characteristics specified in Table 5.1 are not necessarily obtainable simultaneously or in a single system. For example, a single CRT cannot obtain full color with the specified luminance and contrast all in the same display.

While Table 5.1 is useful for a comparison of the technologies over a broad range, it certainly does not give the whole story. In an effort to round out the comparison a verbal summary of the advantages and disadvantages of each technology is included in Table 5.2. This list should be self explanatory. For further information on any issue raised by an entry in the table the reader is referred to the appropriate technology section of Chapter 3.

Several observations can be made following a study of Tables 5.1 and 5.2. The most obvious fact is that the mature CRT technology still dominates in almost all the

Table 5.1 Performance Summary of Display Technologies

Note: Performance limits are not necessarily obtainable simultaneously or in a single display system.

Performance Parameter	CRT	VFD	LCD	PDP	LED	EL	ECD
Max. Luminance (Cd m^{-2}) (active display)	10^5	10^3	-	10^3	10^4	5.10^3	-
Max. Reflectance Ratio (passive display)	-	-	.9	-	-	-	.8
Contrast $C_v = \frac{L_f - L_b}{L_b}$	10	<1	>10	1	1	3	>10
Efficiency (lumens per watt including drive electronics)	5	1	-	.1	.01	.2	-
Dimming Ratio (for active graphics display)	10^7	10^5	-	500	$>10^7$	$>10^7$	-
Typical Resolution (pixels per mm)	20	5	5	3	5	5	5
Max. no. of pixels per picture height	5000	500	1000	2000	500	1000	500
Gray Scales (over full ambient range in $\sqrt{2}$ steps)	10	1	4	4	6	8	4
Viewing Angle (maximum angle in degrees from normal)	80	70	10-80	80	60	80	80
Current Color Capability (M=mono; P=poly; F=full)	F	M	M	M	P	M	P
Storage Temperature Range (degrees C) Can meet:							
A) -55 to +125	A	A	B	A	A	A	A
Uncompensated Operating B) -25 to +80							
Temperature Range (deg. C) C) 0 to +50	A	A	C	A	B	B	B
Current System Cost (per pixel) H - High M - Medium	L	L	M	H	H	L	L
Projected Cost (per pixel) L - Low VL - Very Low	L	L	VL	L	H	VL	L
Operating Life (hours) A) 10,000 hours; B) 5,000 hours	A	A	A	B	B	B	A

Table 5.2 Relative Advantages and Disadvantages

Technology	Advantages	Disadvantages
CRT	High resolution	High voltage
	Good addressability	Large depth
	High contrast	Limited life under high ambient light
	Flexibility	Corner edge focus circuitry
	Color capability	High maintenance cost
	Mature technology	Heavy
	High luminous efficiency	
VFD	Good reliability	Poor in high ambient light
	Mature technology	Limited ability for large matrix display
	Low production cost	Vibration sensitive
	Low voltage	Background glow (in some cases)
LCD	Passive display	Slow switching speed (in most cases)
	Low switching voltage	External illumination required
	Very high resolution possible	Temperature range
	No contrast loss in high ambient	Low yield
	Inherent memory possible	Addressing, multiplexing, viewing angle, and contrast can be problems
PDP	Inherent memory possible	Poor in high ambient
	High resolution	Generally orange
	No flicker for most	Limited dimming range
	High contrast ratio	Background glow (some cases)
	Rugged	
	Wide viewing angle for most	
	High MTBF	
	May be made transparent	
	Mature technology	
LED	Extremely fast	Short persistence
	High resolution	Poor luminous efficiency
	Rugged	Difficult to get uniform brightness
	Reliable	High peak currents
	Low voltage	No blue
		Expensive in large arrays
		Yield problem
EL	Rugged	Moderate luminous efficiency
	High contrast (black layer)	Moderate luminance
	Uniformity of brightness	
	Large size potential	
	Potentially low cost	
ECD	Passive display	External illumination required
	High contrast	Difficult to matrix address
	Inherent memory	Need more stable electrodes and electrolyte
		Slow switching speed

performance measures with the notable exception of future projected cost per pixel. CRT is the only technology with full, current, color capability. The disadvantages of CRT are not extremely serious. LCD and EL have the potential for very low, future cost. However, cost is difficult to quantify and ultimate cost will depend heavily on applications in industries other than aerospace, particularly those associated with consumer products such as TV, watches, calculators and computers. When the other technologies are compared with CRT there is always at least one parameter where they perform poorly relative to the CRT. Those observations should be tempered by the fact that the performance comparison did use a standard application in which the CRT performs very well.

5.3 REQUIREMENTS FOR APPLICATIONS

The applications of electronic display technology to military aircraft are classified in Chapter Four. The ultimate goal is to make an assessment of the potential of each technology to satisfy the requirements of those specific applications. As an intermediate step it is desirable to identify the particular performance parameters which are important to each application. Of course, all the parameters can be important but some are more significant than others. At the outset maximum luminance was of such overriding importance that it was necessary to further break down the applications by specifying whether each would have to operate over the full range of ambient including direct sunlight or whether it would only have to operate over a restricted range of ambient such as that associated with a rear cockpit or internal cabin. In the latter case the requirement on maximum luminance is reduced. The head-up and helmet-mounted displays are always expected to meet the full range of ambient requirement unless restricted to night operations, where dimming ratio becomes of primary importance. The resolution parameters including gray scales are of major importance in the video and vector graphic applications. Efficiency is of major importance for helmet-mounted displays because of the undesirability of heat generation. Color capability has been discussed in 2.4. In general, it is difficult to prove a requirement for color other than the motivation provided by the fact that pilots prefer color. Cost and long life are generally desirable features. High speed is desirable in video applications. Inherent memory is often desirable for the message and discrete applications.

5.4 TECHNOLOGY POTENTIAL

The major goal of this work has been to make an assessment of electronic display technology for military aircraft applications. To that end Table 5.3 has been prepared as a summary of the findings. While the kind of information contained therein is of major value to the users, it has not been easy to generate. The reason for the difficulty is that to be accurate it is necessary to predict the future. The numbers 1-5 were used to score the technology with the interpretation of each number as shown. Each member of the working group had the opportunity to prepare his own grade sheet at his leisure and with outside consultation. Then, in executive session, individual grades were combined to form a single set. There were considerable differences of opinion and the results represent a majority decision that was not always unanimous. While there was some individual bias, the group as a whole made every effort to be fair and consistent in their assessment. A study of Table 5.3 permits a number of observations to be made. The large number of ones associated with the CRT confirms the earlier observation that it is currently the dominant technology. The only applications where the CRT is not currently used are for the keyboard and alpha numeric classifications where the CRT is not expected to find use. Also as already observed there are major differences in the technology potential depending upon whether the application requires operation over the full range of ambient. PDP, for example, as a mature technology is either qualified for, or in use in, almost all those applications except where a full range of ambient is specified. LCD does well in high ambient although extra illumination is required to

Table 5.3 Application Assessment

	Applications																			
	Full range of ambient (front cockpit)												Restricted range of ambient (rear cockpit)							
Display Technologies	Video HUD	Vector-graphic HUD	Video HDD	Vector-graphic HDD	Video HMS	Vector-graphic HMS	Vector-graphic MMD	Message MMD	Message Keyboard	Discrete Keyboard	Message Alphanumeric	Discrete Alphanumeric	Video HDD	Vector-graphic HDD	Vector-graphic MMD	Message MMD	Message Keyboard	Discrete Keyboard	Message Alphanumeric	Discrete Alphanumeric
CRT	1	1	1	1	1	1	1	1	5	5	5	5	1	1	1	1	5	5	5	5
VFD	5	5	5	5	5	4	4	3	3	3	3	3	5	5	4	3	3	3	3	3
LCD	3	3	3	3	3	3	3	3	3	3	2	1	3	3	3	3	3	3	2	1
PDP	5	5	5	5	5	5	5	5	5	5	5	5	5	1	1	1	1	2	1	2
LED	5	5	5	4	5	3	3	3	3	3	2	1	5	2	2	2	2	2	1	1
EL	5	4	4	3	3	3	3	3	3	3	3	2	3	3	3	3	2	2	2	2
ECD	5	5	5	5	5	4	4	4	4	3	3	2	5	5	4	4	4	3	3	2

1 - Technology is <u>now</u> used in this application.
2 - Technology is qualified for this application.
3 - Technology could be qualified for this application in 5 years.
4 - Use of technology for this application is possible in longer time frame.
5 - Technology unlikely to find use here.

take care of veiling luminance when bright external light comes from in front of the aircraft. Both LED and EL are more promising for the applications where they do not have to operate in high ambient. VFD is poor in high ambient light and, in general, is not yet promising for any of the applications. LCD as a passive display has the potential to qualify for all the applications. ECD which is also passive is generally not promising for the video applications primarily because of its slow switching speed and matrix addressing difficulties. The most promising of the new technologies are LCD, LED and EL. Comparing those three, LED appears to be the furthest developed at this point, but is not expected to find application at the video level. LCD has the edge in high ambient. Both LCD and EL hold promise for very low cost. It is difficult to pick an obvious winner among the three. Each technology has its own strong proponents based to some extent on how much they have invested in their technology choice.

5.5 SUMMARY

A comprehensive study of current modern display technology has been completed. The report contains an explanation of the technical and human factors which affect visual display design. Specific technologies have been reviewed in depth. The applications for displays in military aircraft have been classified and explained. An assessment of the potential of each technology to qualify for the applications of interest has been made.

The CRT is and will remain for some time at the forefront of display technology for applications in military aircraft at the video end of the spectrum where operation is required over the full ambient range. The newer flat panel technologies will find their applications first at the message and discrete data end of the spectrum where the display needs to operate only over a restricted range of ambient light. PDP is the most mature of the new flat panel technologies and has already found application in military aircraft. It lacks potential for high ambient and video applications. It also has limited dimming range. LCD, LED, and EL are the more promising new contenders of the flat panel technology group, and it is difficult to pick a winner among the three. LED is the most developed. It is promising for its speed and resolution capability. It appears to be limited by poor luminous efficiency, its lack of blue color, and its higher cost in large arrays. LCD and EL show the greatest promise for very low cost. LCD has high resolution, however, an LCD video display is a long way from operational. Prospects for improvements are good through development of complex drive systems, special filters and temperature compensation. EL shows considerable promise but is expected to obtain only moderate luminance and luminous efficiency. VFD and ECD are expected to find only limited application in military aircraft. VFD appears attractive to the automobile market but is inadequate in high ambient. ECD is only in an advanced state of laboratory development. It is presently limited by slow switching speed and instability of electrodes and electrolytes. In summary, there are many continuing challenges to be met by modern display technology for applications in military aircraft, but the potential is very promising over the long run.

GLOSSARY OF TERMS

ACCOMMODATION - Adjustment of the focus and the binocular angle of the eyes, for a given viewing distance.

ACHROMATIC REGION - The area of a chromaticity diagram around x = y = 0.33, in which acceptable "white" reference points are located.

ADAPTATION - Adjustment of the pupil aperture and light-sensing sensitivity of the eye-brain system to a given ambient luminance level.

ADDRESS - A label (binary number) allocated to a location where data is stored.

ALIASING - When a signal of frequency fi is sampled at a frequency fs (temporal or spatial frequencies), two components fs - fi and fs + fi appear. In the case of an image with a periodic structure looked at through a device with another periodic structure (i.e. multiplied by this other image), the result is known in optics as a moiré pattern (french word for english mohair).

ANGULAR DEPENDENCE OF CONTRAST - Common liquid crystal displays show a variation of contrast depending on the viewing angle of the display.

ANISOTROPIC - Showing different properties (e.g., velocity of light transmission) in different directions.

ASPECT RATIO - The ratio of width to height of a display surface. The standard television aspect ratio is 4:3.

BACKGROUND GLOW - Parasitic light emitted, diffused and/or reflected by non-selected display area.

BIREFRINGENCE - The property of a material whose refractive indices depend on the plane of polarization of light passing through it.

BLACK BODY- A radiator of uniform temperature whose radiant flux in all parts of the spectrum is the maximum obtainable from any radiator at the same temperature, and which absorbs all radiant energy that impinges on it.

BLOOMING - In a CRT the region of the display where luminance is excessive due to an enlargement of the spot size and halation of the phosphor surface.

BRIGHTNESS (luminosity) - Attribute of visual sensation according to which an area appears to emit more or less light. Its psycho-physical, photometric equivalent is luminance. Brightness is often confused with luminance.

BUS - Lines and circuits for high traffic data and address transmission.

CANDLE POWER - Luminous intensity expressed in candelas.

CHARACTER - A letter, numeral or graphic symbol contained in a character block or field composed of fixed numbers of lines and columns of pixels.

CHOLESTERIC - A class of liquid crystal materials in which the elongated molecules are parallel to each other within the plane of a layer, but the direction of orientation is twisted slightly from layer to layer to form a helix through the layers; this material has a high rotatory power.

CHROMATICITY - The color quality of light, defineable by its dominant wavelength and purity taken together; or by its x, y coordinates on the CIE chromaticity diagram.

CHROMINANCE - Colorimetric difference between the observed stimulus and a reference stimulus of a given (a)chromaticity at the same luminance; expressable as the product of the chromaticity difference and the luminance.

COLOR CONTAMINATION - An error of color rendition due to incomplete separation of the color components of a display.

COLOR DILUTION - A reduction in the purity of a color by the addition of white light.

COLOR EDGING - Extraneous colors appearing at the edges of colored images.

COLOR PURITY - A psycho-physical measurement of the degree to which a color is free of white light. Its psycho-sensorial equivalent is saturation. The term is also used to define the absence of color dilution/contamination in the operation of a colored display.

COLOR TEMPERATURE - The temperature to which a black body must be heated to produce a color matching that of the source. The unit is the Kelvin (K).

CONE - A flask shaped nervous cell in the retina, sensitive to bright light and color. Color vision is entirely a function of cones.

CONTRAST (luminance) - There are a number of contrast definitions depending upon the application, see section 2.1.2.

CONTRAST RATIO - The ratio between the maximum and minimum luminance values of a display in its environment.

CONTRAST (color) - No internationally agreed definition available.

CONTRAST SENSITIVITY - Officially: the reciprocal of the minimum relative luminance $\frac{\Delta L}{L}$ perceptible. In practice often the reciprocal of the just perceptible modulation depth (MD) of a harmonic grating of given spatial frequency.

CRITICAL FLICKER FREQUENCY - The critical flicker frequency or flicker fusion frequency is the frequency of a harmonically modulated local luminance above which no rhytmical sensation is perceived. The CFF typically is about 60 Hz, but depends upon adaptation, the position in the field of view, and upon the response characteristics of the emitting or reflective material of which the display is made.

DEDICATED DISPLAY - Device capable of displaying only one variable or parameter.

DICHROIC - Property of materials with absorption depending upon the plane of polarization of transmitted light.

DOMINANT WAVELENGTH - The wavelength of a light of a single frequency which matches a given color when combined with an appropriate amount of a reference "white" light.

FECHNER'S LAW - The intensity of a sensory response is generally proportional to the logarithm of the stimulus intensity. The luminosity system of measurement serves to linearize this effect for visual stimuli.

FIELD - One of the two (or more) equal parts into which a display frame is divided in an interlaced scanning system, the first field containing the even-numbered lines, and the second field containing odd-numbered lines. Thus for a field frequency of 60 Hz the frame frequency is 30 Hz. The odd and even lines which form the complete frame are said to be interlaced. In night viewing systems and some types of color display the image can be made up of several fields, internally interlaced or not, displayed adjacent to each other; or interlaced at a high order. This need results from the properties of the eye, of the source, of the detector and of the signal processing scheme.

FLICKER - If the eye perceives that a display is periodically energized by two or more different stimuli (brightness, hue, saturation) in a fixed sequence the display is said to flicker. The flicker frequency equals the refresh rate of complete sequence fields.

FLICKER FUSION FREQUENCY - see critical flicker frequency.

FONT - Basic geometry and style of a set of alpha-numeric characters. In dot-matrix systems the font is adapted to the grid of a character block or -field, typically 5 x 7 (e.g. Huddleston) or 7 x 9 (e.g. Lincoln-Mitre).

FOOT-CANDLE - A non SI unit of illumination equal to the illumination which occurs when uniformly distributed luminous flux impinges on an area at a density of one lumen per square foot.

FOOTLAMBERT - A non SI unit of luminance equal to the uniform luminance of a perfectly diffusing surface emitting or reflecting luminous flux at the density of one lumen per square foot.

FORMAT - A selection of type (font) and arrangement of symbols and characters.

FOVEA (centralis) - A depression toward the center of the retina, the point where the vision is most acute. Mostly cones are present in this area of the retina.

FOVEOLA - A rodless small part of the fovea, located at the point of regard.

FRAME - With both raster and cursively-written CRT's and with all types of matrix-addressed displays, the displayed information is re-written on the display surface at a field rate which is generally sufficiently high to prevent flicker. One complete cycle of the field sequence is termed a "frame"; the information content used to form the display is also sometimes known as a frame, hence "frame-store" for a store containing this information.

GAMMA - In case of a display, the power exponent used to approximate the curve of display-luminance output versus signal-input amplitude.

GRAPHIC DISPLAY - Bilevel (B/W and color) display of graphic information.

GRAY SCALE - Variations in the luminance value of achromatic or monochromatic light. Shades of gray are generally defined as gray-scale graduations that differ by the square root of 2.

HEAD-UP DISPLAY - A display in an aircraft cockpit arranged so that the symbology is collimated to infinity and appears to be superimposed upon the view of the real world ahead of the aircraft. It is usually used in military aircraft as a weapon-aiming display, and as such is a derivative of the gunsight, but it has also been used in civil and military aircraft as a landing aid.

HELMET-MOUNTED DISPLAY - Similar to a head-up display since the symbology is collimated and appears superimposed on the view of the outside world. It is very small and light weight to enable it to be carried on a flying helmet, and is frequently used in conjunction with a pickoff which measures the attitute of the helmet relative to the aircraft.

HEAD-DOWN DISPLAY - Used to describe displays mounted below the instrument panel coaming.

HOMEOTROPIC ALIGNMENT - When the optic axis of the liquid crystal is aligned normal to the cellwalls.

HUE - Hue is the attribute of a visual sensation which is expressed by different color names such as red, yellow, green, blue, purple, etc. It is related to the colorimetric quantity dominant wavelength.

ILLUMINANCE (or illumination) - The illuminance of a surface is the luminous flux (or quantity of light per second) falling on unit area.
Unit: lumen per square metre (lm m^{-2}) termed lux.

INTERLACE - A method of raster-writing CRT displays to trade off flicker and bandwidth. In a 2:1 interlace, alternate fields are written such that a field formed of even lines is followed by a field formed of odd lines.

ITO-LAYER - Acronym for Indium-Tin-Oxide layer, semiconducting material; optically transparent in thin layers (100 Å). Used as transparent electrode material for various types of displays. Prepared onto glass substrates by various vacuum deposition techniques (e.g. sputtering, evaporation).

LAMBERT - A unit of luminance equal to the uniform luminance of a perfectly diffusing surface emitting of reflecting light at the density of one lumen per square centimeter.

LINE - Single line in a matrix display structure which, in combination with a single column, addresses one picture element.

LUMINANCE - The luminance of a surface emitting or reflecting or transmitting light is the luminous intensity per unit apparent area.
Unit: candela per square metre (cd m^{-2}).

LUMINOSITY - The luminosity (or brightness in the US) is the attribute of visual sensation which expresses whether an area appears bright or dim.

LUMINOUS FLUX - Luminous flux is the rate of flow of radiant electromagnetic energy (or quantity of energy per second) evaluated according to its ability to produce visual sensation of light in the average human eye.
Unit: lumen (lm).

LUMINOUS INTENSITY - The luminous intensity of a source in a given direction, is the quotient of the luminous flux leaving the source, propagated in an element of solid angle containing said direction, by the element of solid angle.

LUX - The unit of illuminance. One lux equals one lumen per square meter.

MATRIX ADDRESSING - The selection of a picture element by the coordinated application of
(orthogonal) signals on two orthogonal sets of addressing lines.

MEASURAND - Variable of known structure and dimension of which the magnitude (and phase, if applicable) must be determined by the act of measurement.

MESOMORPHIC - A state of matter intermediate between a crystalline solid and a normal isotropic liquid, and in which long "rod-shaped" organic molecules contain dipolar and polarizable groups.

MODULATION DEPTH - Ratio of the difference between peak and average signal (luminance) over average signal (luminance). With foreground luminance L_f and background luminance L_b, and for symmetrical modulation, the modulation depth MD = $(L_f-L_b)/(L_f+L_b)$.

MODULATION TRANSFER FUNCTION - In the case of analogue imaging systems (both the spatially continuous and sampled), the MTF is a parameter describing the ratio of output to input contrast. The MTF is a function of spatial frequency. Spatial phase information (e.g. displacement) is not accounted for. In the case of displays it is also the ratio of the spatial MD at the display face to the MD of the driving (input) signal.

MONOCHROME - Any combination of colors of the same dominant wavelength, but of different purities and luminances.

MULTIPLEXING (time division) - The combination in a sequential manner of a number of single, independent, input signals onto a common channel or: the sequential separation of data carried by a common channel onto a number of single, independent, outputs (e.g. pixels).

NEMATIC PHASE - A phase of a liquid crystal in the mesomorphic state, in which the liquid has a single optical axis in which the molecules are aligned in one direction, appears to be turbid and to have mobile threadlike texture, can flow readily, has low viscosity, and lacks a diffraction pattern. This phase can be oriented by a magnetic or electric field.

PARAMETER - Constant or quasi static coefficients or set points of a system which determine the rate (of variables in), or initial conditions of, a process carried out by the system; are quantifiable by a suitable mapping onto a set of rational numbers.

PEL - see picture element.

PERCEPTION - Complex appearing in the field of consciousness and made of sense impressions supplemented by the memory.

PHOSPHOR - A substance capable of luminescence when excited by an energy source (e.g. accelerated electrons, an electrical field, electromagnetic waves).

PHOTOPIC VISION - The eye-brain response with the light adapted eye, to luminance levels sufficient to permit the full discrimination of colors: daylight vision, in contrast to twilight of nighttime vision. Is mainly attributable to retinal cones.

PICTURE ELEMENT - The smallest segment of a matrix or a raster line which can be discretely controlled by the display system. Also called a pixel or pel.

PIXEL - see picture element.

POINT SPREAD FUNCTION - The function which describes the spatial smearing of a point source of light.

PRIMARY COLORS - Colors of constant chromaticity which are mixed to produce or specify other colors.

PRIMING - In a plasma display panel, the creation of free ions and electrons and eventually UV radiations in specialized (generally hidden) cells in the neighborhood of the display cells, in order to ease their ignition when a striking (or firing) voltage is applied.

PROGRAMMABLE DISPLAY - Device on which a variety of symbology can be shown at will.

RARE EARTH-DIPHTALOCYANINE - Organic electrochromic material, molecule showing a so called sandwich-structure: two complex planar organic structures are sandwiching a rare earth atom like Lutetium or Dysprosium. Used in preparation of electrochromic electrodes by sublimation of the material on ITO substrates.

RASTER - The pattern of vertical and/or horizontal lines or dots formed on an image independently of that image, but determined by the display or printing technology.

RASTER SCAN - The pattern of written horizontal scanning lines formed on a (TV) display surface when no signal is being received (geometrical structure as opposed to field and frame which are temporal structure).

RETINA - The innermost coat of the back part of the eyeball consisting of a layer of nervous cells (rods and cones) sensitive to light which are terminations of the optic nerve.

RESOLUTION - A measure of the quantity of information that may be displayed and resolved (separated) on a screen of any kind. It can be expressed in terms of number of spots, TV lines, line pairs, cycles, pixels, bits, either per picture width or per picture height or per frame, per field or per unit length

RODS - Rod-shaped nervous cells in the retina, sensitive to dim light, but insensitive to color. Therefore the dark adaptation of the eye is accompanied by a loss in color perception.

ROW - Set of lines belonging to a string of characters as opposed to a single line of the display structure.

SATURATION - The saturation of a color sensation is the impression of the amount of pure color present. The maximum saturation is perceived when a spectral color is viewed at adequate luminance, and minimum is when a white surface is viewed. The psycho-sensorial equivalent is purity.

SCANNING - The process of successively addressing points on a display surface, either stroke/vector writing per symbol or in a fixed pattern as in raster scanning or PPI radar (ρ,Θ).

SCOTOPIC VISION - The eye-brain response of the dark adapted eye to luminance levels below that required for the full discrimination of colors; effected only by rods. Twilight and night vision, in contrast to photopic or daylight vision.

SEDIMENTATION - Separation of the solid particles and the liquid phase of a suspension. Colloids show sedimentation (coagulation) after destabilizing treatment (e.g. adding strong electrolytes).

SHADING - An unintentional large-area luminance gradient in a display.

SMECTIC PHASE - A form of mesomorphic liquid crystal state in which liquid motion is more of a gliding than a flowing nature, drops are often formed which exhibit a series of fine lines, especially under polarized light. X-ray diffraction patterns can be obtained in only one direction.

SPATIAL FREQUENCY - Number of cycles of a harmonic grating per unit distance or solid angle (cycles per mm, cycles per degree).

STANDARD ILLUMINANT - One of several reference "white" colors specified in such a way that its energy distribution is reproducible.

STANDARD OBSERVER - A hypothetical observer with a visual response possessing the colorimetric properties defined by the 1931 CIE tables of distribution coefficients and chromaticity coefficients of the equal-energy spectrum.

STERADIAN - A unit of solid angle, defined as the solid angle subtended by an area r^2 on the surface of a sphere with radius r.

SURFACTANT - Additive to the liquid phase of a colloidal suspension. In solution, the ions formed by the surfactant are adsorbed on the solid particles leading to an electrostatic repulsion between the particles, thus preventing coagulation (aggregation of colloid particles forming large particles) and sedimentation.

SUSPENSION - Mixture of a liquid and solid particles.

TEARING - A condition in a raster-scanned display in which groups of horizontal lines are displayed in an irregular manner.

TWINKLE - Vertical jump phenomenon by successive display of pixels on lines belonging to different fields in an interlaced rasterscan image.

TRANSFER OF DISCHARGE - By way of the priming effect, unique to plasmas, a glow discharge may be transfered from one cell to another by application of appropriate voltages between their own electrodes (and eventually one or more auxiliary ones) (see section 3.4.4.2).

TURBIDITY - State of being turbid, i.e. appearing cloudy or muddy due to suspended articles. In the case of an LCD in the nematic phase, scattering of the light is brought about by the application of a high electric field.

VARIABLE - Dynamic or quasi, static intensity or quantity which can be enumerated by a mapping onto a set of rational numbers.

VIOLOGEN - Organic electrochromic material:
e.g. 1,1'-diheptyl - 4,4' bipyridil bromide (salt with an organic cation); commonly used in an aqueous solution and subsequently electrochemically precipitated on an electrode.

VISUAL ACUITY - The capacity of the eye-brain system to discriminate objects which are very close to each other. Nominal value for visual acuity VA (photopic condition) is 1 minute of arc. VA is expressed as the reciprocal of the discriminable angle.

WEBER's LAW - The approximate luminance difference threshold ΔL is a constant fraction of the adaptation luminance L over a wide (photopic) range.

LIST OF ABBREVIATIONS

- ADI	Attitude director indicator.
- ASCII	American standard code for information interchange.
- CFF	Critical flicker frequency.
- CIE*	Abbreviation for the Commission Internationale de l'Eclairage, also referred to as the International Commission on Illumination (ICI).
- CTF	Contrast transfer function.
- DKDP	Deuterated potassium di-phosphate.
- ECD	Electrochromic display.
- EDD	Electrodeposition display.
- EHT	Extra high tension (voltage on CRT's etc.).
- ELD	Electrolytic display.
- EMI	Electromagnetic interference.
- EPD	Electro phoretic display.
- EL	Electroluminescence.
- FLIR	Forward looking infra red.
- HDD	Head down display.
- HMD	Helmet mounted display.
- HMS	Helmet mounted sight.
- HSD	Horizontal situation display.
- HUD	Head up display.
- I/O	Input/output.
- ITO	Indium tin oxide.
- JEDEC**	Joint electron device engineering council.
- LCD	Liquid crystal display.
- LED	Light emitting diode.
- LOS	Line of sight.
- MD	Modulation depth.
- MFK	Multi function keyboard.
- MIM	Metal insulator metal.
- MMD	Mission management display.
- MPD	Magnetic particle display.
- MOS	Metal oxyde semi-conductor.
- MTF	Modulation transfer function.
- MTFA	Modulation transfer function area.
- PDP	Plasma display panel.
- PFE	Photo-ferro electric.
- PLZT	Lead lanthanum zirconate titanate.
- PSF	Point spread function.
- RAM	Random access memory.
- ROM	Read only memory.
- TFEL	Thin film electro-luminescence.
- TFT	Thin film transistor.
- TTL	Transistor-transistor logic.
- VFD	Vacuum fluorescence display.
- VSD	Vertical situation display.

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14. Abstract

The intent of this AGARD Report is to:

- Analyse both current and anticipated requirements for information displays in military avionics.
- Identify display applications where new technologies in visual displays have the greatest impact on military avionics.
- Survey the present status and potential for further development of a wide range of modern display technologies.

An engineering view on vision and displays explains the technical factors affecting the perception of displayed data, sampling and addressing, the human factors affecting display design and use, and the use of color in displays.

A description of technologies includes the cathode ray tube, vacuum-fluorescent tubes, liquid crystal displays, light emitting diodes, electro-luminescent displays, electrochemical displays, and other display technologies. The application of display technologies to military avionics is examined in the areas of classifications, head-up displays, head-down displays, helmet-mounted systems, keyboard displays, and alphanumeric modules. An assessment is made of modern display technology potential.

Reference listings resulting from a comprehensive review of recent work in display technologies are also provided.

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