A DARK TRACE, LARGE SCREEN DISPLAY

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S.J. Mildenberger

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Student: S. J. Mildenberger Supervisor: Dr. A. R. Boyle

ABSTRACT

A feasibility study of dark-trace cathode ray tubes for large screen display of high resolution cartographic data,is described. Following a comprehensive study of various display methods, optical projection of dark trace tube images was chosen for experimental investigation. Various types of cathodochromic targets and optical systems were studied. It was found that a satisfactory system could not be constructed using available components, but would require the design of a unique CRT target and optics system.

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INTRODUCTION

A system for computer-aided editing and manipulation of cartographic data was under development in the Electrical Engineering Department at the University of Saskatchewan and the need for a large screen, high resolution display became apparent. The largest storage display available at that time was the Tektronix 611, which had only 1000 by 800 addressable points over a viewing area of 20 cm. by 25 cm. Although this limited area was not a major restriction to the usefulness of the cartographic system, nevertheless it was considered that the assessment of the editing work could be aided considerably if the final product could be pre-viewed at the size and detail which would be finally printed. However, an interactive display having the necessary size and resolution for such an application did not exist. It was, therefore, decided to investigate the feasibility of building such a device.

The ability of a cartographic editing system to serve as an efficient but inexpensive tool for the preparation and manipulation of digital map data already has been achieved through the optimized integration of sophisticated software with state-of-the-art hardware, neither of which could be greatly altered without having a detrimental effect on the system's operation. The selection of a technology which could yield a satisfactorily large screen display was dictated, therefore, not only by the needs of the operator, but also by the software and hardware constraints of the existing system. An evaluation (Appendix One) of the system indicated that, to be useful, the display needed to fulfil seven basic requirements. These were:

1. a minimum viewing area of 100 cm. by 130 cm.,
2. a minimum screen resolution of 10 points per mm.,
3. a minimum addresseable resolution of 20 points per mm.,
4. point-at-a-time addressing capability,
5. a purchase price not exceeding $20,000 and a negligible operating cost,
6. a maximum time of two minutes to erase and redraw an image, and
7. the capability of storing an image for not less than one hour.

These specifications differed from most commercial display requirements in two ways. In the first place, the combination of a large viewing area and a high resolution image exceeded the requirements for the majority of display applications. Secondly, an erase time of two minutes had been unacceptably slow for most systems. Because of the uniqueness of the mapping conditions, it was considered worthwhile to examine the suitability of dark trace materials. They were well known for their ability to store an image of a resolution higher than most other display materials. However, because of the slow thermal erase cycle which was necessary for fatigue-free operation, these dark trace materials had received very limited attention. Thus, there existed a field of display technology which had not been fully explored and which, it was hoped, would result in the development of a unique and useful display system.

The feasibility of a 'Large Screen, High Resolution Display' is examined in this thesis. Both 'large screen' and 'high resolution' are ambiguous terms which appear frequently, and with a variety of meanings, in the published literature on display devices. These terms must, therefore, be defined within the scope and context of this thesis.

The term 'large screen' is generally applied to any display with a viewing area larger than that which can be produced on the limited imaging surface, or face plate, of a cathode ray tube. Such a device must use another technology instead of, or in addition to, the cathode ray tube, in order to produce the displayed image. Although every application is unique, large screen displays can be broadly classified under two categories: those intended for group viewing, as in situations where a display the size of a television monitor is too small; and those intended for individual viewing of a large detailed image. The requirements of the user, and hence the technical demands in these two types of displays, are usually quite different. The former tends to require low resolution, high brightness, and no interactive communication with the viewer; the latter requires very high resolution and at least limited interactive capability. The following discussions deal exclusively with the second type of display and all references to user requirements, technical specifications, and display capabilities are used in this context.

The resolution of a display must be defined both in terms of the number of addressable points across the width of the display, and in terms of the number of resolvable points across this distance in the viewed image. Either value is usally classified in the literature as 'high' if it exceeds twice that of standard televsion, or more than 1000 lines or points across the viewing surface. However, for the cartographic display being researched here, a resolution of more than 10,000 resolvable lines and 20,000 addresseable points is required. Thus, the term 'high resolution', when used with respect to this display, refers to the 'very high resolution' and the associated technical difficulties demanded by these unique display specifications.

It was necessary to examine the state-of-the-art in other display technologies in a continuous manner as the research proceeded. During the past five years, work in these areas had been advancing very rapidly and it was possible that a display which would satisfy the requirements of cartography had in fact, already been developed. Had this been the case, the present research might have been economically unjustifiable from an engineering point of view. A summary of the state-of-the-art in existing display technologies is, therefore, presented in Appendix Two.

The bibliography presented in this thesis includes references for most of the published papers concerned with cathodochromic displays. References to articles on the physics of cathodochromic materials, and also to other display technologies have been chosen which will direct the reader not only to information on these topics, but also to further more extensive bibliographies included in many of the referenced papers.

CHAPTER ONE

AN INTRODUCTION TO DISPLAY TECHNOLOGY

The computer can be an invaluable tool for the manipulation of graphical data, provided the man and the machine have a suitable method of communicating with each other. The most efficient interface for this purpose is an interactive display but, because of technical and psychological limitations, the display system which can actually be achieved usually falls far short of that which is optimum for the purpose.

There exists very little knowledge of how the human eye and mind accept and process information. Few methods have been learned of avoiding or reducing the many limitations imposed by the human visual system on the optical information which can be presented usefully by a display device. Thus, the visual properties which a display must exhibit,are almost totally subject to the apparently inflexible psychological and physiological traits of man. Properties such as colour, contrast, brightness, resolution, size, and data presentation rate must meet certain minimum criteria, otherwise the display is of limited practical use. This makes man a very difficult 'device' with which to interface.

The computer to which man must be interfaced also presents constraints; many of these occur as a result of previously developed, and relatively inflexible, hardware and software. The resulting specifications for an interface between the computer and the viewer often imply expensive, difficult, and sometimes unachievable technical requirements. Inevitably, this results in drastic compromises of the desired input and output characteristics for the display. It is only by an analysis of the desired characteristics, then of the interface technology available to achieve them, and finally of the resulting compromises which must be accepted, that the feasibility of a display for a particular application can be determined.

1.1 Interfacing to the Human

The visual display properties of size, resolution, contrast, brightness, and flicker rate are intricately interdependent, both in terms of the technical methods of their generation in a display device, and with respect to their acceptability as determined subjectively by the viewer. Although values can be defined for each of these properties which would be adequate for most display applications, it is technically impossible to develop a display device which is capable of simultaneously producing all, or even most, of these optimum values. Furthermore, for devices in which any of the viewing properties approach marginal values, the viewing quality of the resulting displayed image cannot be predicted accurately. It is, therefore, necessary to qualify any predictions regarding the acceptability of a new display device with experimental tests.

The visual properties which are strived for in the design of a display device, and some of the technical difficulties and compromises which must be coped with, are discussed here. Descriptions can be found in references 255 and 257 of the human characteristics on which these technical specifications are based.

1.1.1 Display size and resolution

The optimum resolution and viewing dimensions of a display are a function of the type and quantity of data to be presented, and of ergonomic and psychological considerations. In the case of the cartographic application, little practical experience has been obtained with interactive systems, which would indicate values of size and resolution that might be desirable or acceptable. It is necessary, therefore, to resort to manual experience for these figures. The maximum size and resolution which are simultaneously encountered in hand-drawn maps are beyond the limits of present display technology. Hence, compromises of the desired viewing properties are necessary. Appendix One describes the criteria considered in arriving at the specifications of size and resolution given in the introduction.

Two major constraints present themselves when the design is attempted of a display incorporating both a large area and high resolution. One of these restrictions is a bandwidth limit, imposed by the present state-of-the-art in the technology being considered, or in some cases resulting from theoretical considerations. When this bandwidth limit is expressed in terms of the time required to draw or to refresh a complete image, many display technologies are found to fall hopelessly short of meeting the specifications required for the cartographic application.

The second limitation is one of resolution. The maximum resolution achieved in electrically addressed analogue display systems is approximately 60,000 points, while associated optical systems, which are frequently required, often fall short of this figure. Digitally addressed display devices are limited at present to about one thousand points. Some mechanical devices can produce much higher resolution, but only at the expense of introducing other limiting factors, such as thermal instability, low bandwidth, or restricted formats. As a result, if very high values of size and resolution are specified for a display device, the number of technologies which may be considered is extremely limited.

1.1.2 Contrast

Contrast is defined technically as the ratio of the light intensity reflected, transmitted or emitted from a bright area of the viewing surface to that from a dark area. The apparent contrast of a display, however, is very subjective, depending upon the colour or colours of light being considered, the contrast distribution of the written points or lines, and the pattern of the information being drawn. In addition, the colour and brightness of ambient lighting can influence the viewer's interpretation of contrast. Although these factors can make an analysis of contrast difficult, a contrast ratio of 100 : 1 generally provides as large a range of contrast as can be detected by the eye and thus obviates the need to consider the difficulties listed above.

There are many situations for which reduced contrast is unavoidable. In these cases, manipulation of the spectral width and position of the viewed light can be advantageous in obtaining a visually acceptable image. The eye is most sensitive to green light (figure 1.1). Thus, if the light emitting, reflecting, or absorbing band which generates the image is narrower than the entire visual spectrum, maximum contrast can be achieved by causing this band to peak at the green wavelength of 555 nm. Should the band be very narrow, further improvement might be gained by using optical filters to reduce the background light contribution from either side of this wavelength. These methods of contrast enhancement would of course not be valid, were a full colour display being considered, as they do change the colour of the image.

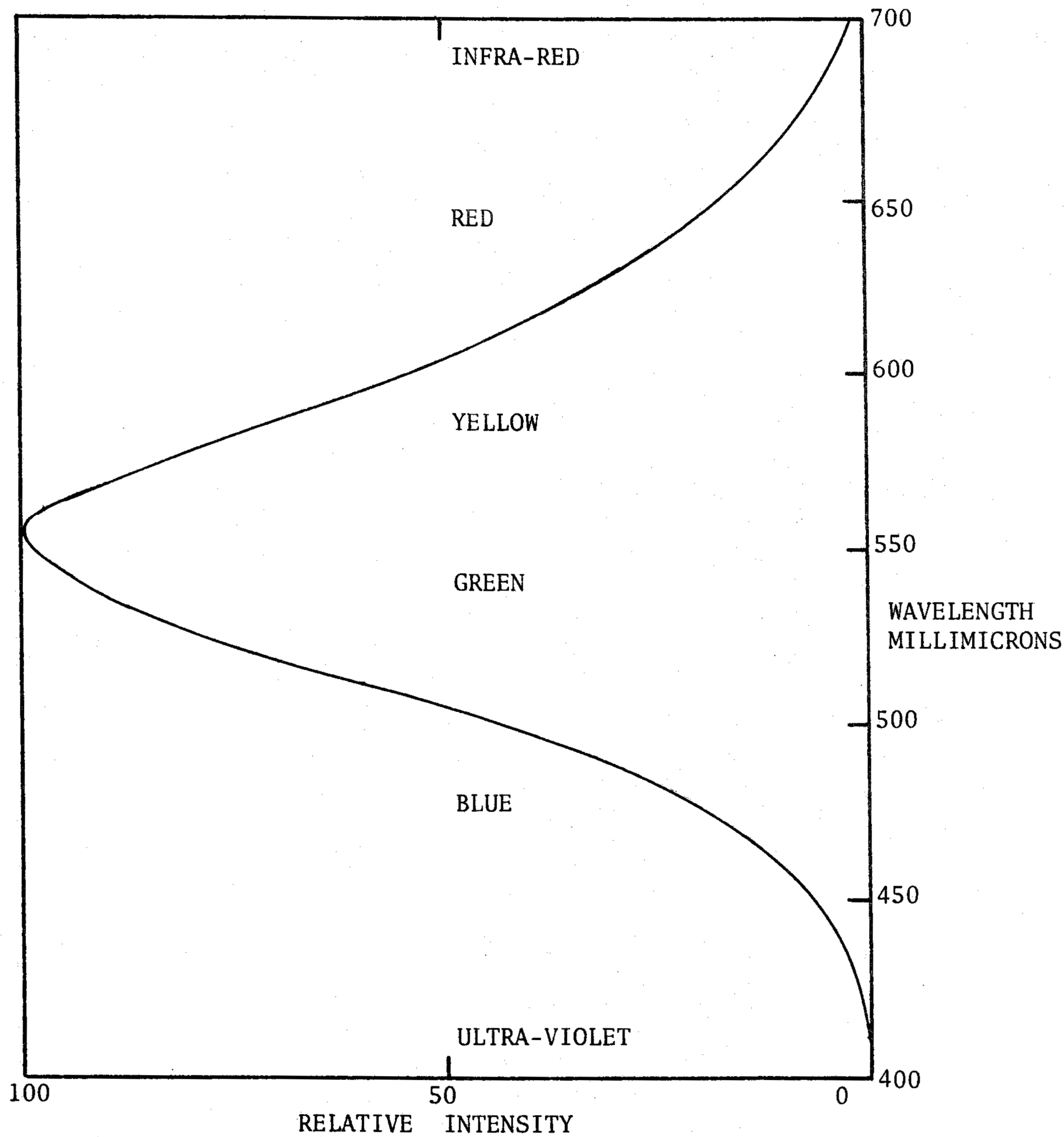

Figure 1.1 Spectral Response of the Human Eye.

The resolution of the displayed image can influence apparent contrast. The eye will interpret greater contrast if adjacent light and dark areas of an image are sharply defined and poorer contrast if these areas merge gradually into one another. Thus, each written point or line should be of constant intensity over its cross-section, rather than being of a Gaussian distribution as is normally generated in display devices, particularly those addressed by laser or electron beams. By using an addressing beam which is of constant cross-sectional intensity, and by employing a target material with a resolution high enough to reproduce the pattern of the addressing beam, the deterioration of apparent contrast can be minimized.

For many applications, it is useful to have the display generate a range of grey levels. A subjective impression of grey levels can be created by varying the number of points per unit area, the size of the points or the colour of the points written on the display. However, grey scale is most effectively accomplished by controlling the intensity (i.e. contrast) of each written point. The number of distinguishable grey scale levels for a specific application cannot be precisely defined, but is a function of the brightness and resolution of the display.[19] For a normal television image, for example, 50 to 100 levels (6 to 7 binary bits of coded information) are necessary to make the shading appear continuous.[20] It appears that 8 bits resolution will probably produce an adequate number of grey scale levels for any display of the size and resolution defined in the Introduction.

1.1.3 Brightness

The brightness of the display is a measure of the visibility and clarity of the display's image in the presence of external ambient lighting. For images which are created by the emission of light, the effect of ambient lighting on apparent brightness is influenced by a complex mixture of factors including not only the ratio of ambient to image brightness, but also the colour or colours of the image, image contrast, and the glare and texture of the screen surface. In situations where ambient light is required, such as for reading maps, the disadvantages of these effects can sometimes be reduced by displaying a blue image while employing red ambient light.

If the displayed image is created by a physical change in the optical properties of the viewed surface, the problem of brightness does not exist. The image appears essentially as a printed picture, exhibiting a higher brightness as the ambient light is increased.

1.1.4 Colour

Many types of graphic information are more usefully and more easily handled if displayed in a variety of colours. The artistic usefulness can immediately be appreciated in the production of maps or graphic art which will be later printed in colour. The operator has the opportunity to view his final product as he creates it.

Colour is also a valuable aid in the generation or editing of most graphical and numerical data. It can highlight important paths or areas in flowchart, circuit or logic diagrams. In map and other data which are presented as numerical values representing a third dimension at the point where the number appears, for example, in depth sounding charts, the use of colour can transmit information much more quickly and concisely to the operator. This is so because, while the human eye cannot pick out a specific number quickly, it can immediately spot an anomaly in a coloured pattern. The use of colour becomes even more indispensible in the presentation of three dimensional graphs because it can illustrate the third dimension with much more clarity than can be achieved by the use of grey scale shading.

If the software and hardware are feasible and the price is acceptable, colour can be a valuable feature for most display applications. However, colour can be difficult to achieve. As has been described above (sections 1.1.1 to 1.1.3), many compromises and manipulations of visual properties may be required in order to obtain adequate brightness and contrast. These are generally incompatible with the design of a full colour display.

1.1.5 Refresh rate

The refresh rate, or flicker rate, influences the viewing quality of any display which does not store an image. This critical frequency, above which flicker cannot be detected by the human eye, is a function of many factors, being higher for increased display brightness, larger image size, lower contrast, shorter wavelengths, younger viewers, and at low brightness, peripheral vision. For most displays, which do not exceed a brightness of fifty foot lamberts, a refresh rate above fifty hertz cannot be detected by the viewer. It is thus necessary to maintain an adequately high refresh rate as any flicker of the image is not only annoying to the user, but also produces mental strain if the operator must spend many hours viewing detailed work.

There are secondary problems which appear even at refresh rates too high to produce apparent flicker. One example of these is the impression that a stationary displayed point will appear occasionally to jump a short distance on the display as the viewer turns his eyes to look at it. This and other undesirable effects are not yet fully understood, but can be disconcerting and annoying when trying to work with high resolution data.

1.1.6 Response rate

The response rate, or speed at which information is presented by the display, must be high enough to prevent long delays for the operator. Once he has requested information, this must be provided within a period of seconds rather than minutes. Merely realizing, while he waits, that the system has found or edited information faster than he could have done manually, will not prevent the user from becoming bored and frustrated, and therefore error prone.

Proper planning of the operator's work, and of the system which carries out his commands, can alleviate this problem in situations where the hardware response time is limited. The delays encountered in redrawing large volumes of data after every data modification can be reduced by such methods as carrying out detailed editing procedures on a faster, although perhaps smaller or lower resolution, subsidiary display. Alternatively, one of two displays might be used for editing while the second is being redrawn. Finally, slow response tasks, such as sorting data and redrawing images, might be accumulated until ten to fifteen minutes response time were required. The operator would then have adequate time to leave the display, either to organize his next work, or for relaxation.

Also of importance to the operator is the ease of interactive communication with the display. He must be able to communicate with the system in a simple and logical manner which is not too alien to one with which he has become familiar while doing the work manually. The machine, in return, must respond by doing exactly as the operator requests, and by doing it as well or better than he could have done by hand.

The physical and psychological limitations of man, coupled with his many idiosyncrasies, make him a difficult item to interface to a machine. This science of matching the machine to the man is still in its infancy and will undoubtedly become yet more complex, but perhaps better understood, in future years.

1.2 Interfacing to the Machine

1.2.1 Data formats

Although every example of data organization is to some extent unique, graphical data must be presented to a display in one of three general forms;raster, vector or single-point format. Each of these has its advantages and disadvantages in terms of speed, cost, computer capability, data storage format in the computer, volume of data to be presented, application of the data, and the display technology being used.

1.2.1.1 raster format

In a raster format, the display is scanned simultaneously in the X and Y axes, while the data are written by modulating the intensity, or Z axis. In order to present data by this method, the data points must be made available to the display in the order in which they will be written. This is not difficult if the data are recorded and stored in a scanned format. However, most graphical data are stored and manipulated as pairs or strings of coordinates. In order to present these data in a raster format, they must first be sorted into scan lines. For even small volumes of data, the sorting process is too complicated for a minicomputer to do in real time, i.e. as the data are being presented to the display. Thus, they must be sorted and stored before the image can be drawn. Although many display systems can cope with scanned format data, it usually is not practical, because of the excessive time required, for the manipulation of large volumes of graphical data such as exist in maps.

1.2.1.2 vector format

Vector formatted data are presented to the display as pairs of X and Y coordinates. Only the start and end coordinates of the line are presented. A vector generator in the display generates a straight line between the two points. This method can cope with data presented as pairs of points and thus, is well adapted to many graphical data formats. If the data consist mainly of straight lines, as in engineering drawings, they can be drawn very rapidly without using a large amount of computer time. The problem which arises with most cartographic data is that many lines are not straight and the usage of a vector generator is inefficient, since very often it is only joining adjacent coordinates.

1.2.1.3 single-point format

In single-point format, as the name implies, all lines or symbols are written as strings of points across the screen. The computer must present each X and Y coordinate pair individually to the display. The drawing speed for long straight lines is slower than in vector format, but for irregular lines the drawing speed is faster. At the same time the extra cost and complexity of the vector generator is avoided.

Single-point addressing requires that the coordinates of every point used to draw a straight line be generated by the computer and presented to the display. The rate of data presentation, i.e. image drawing time, may be limited by the speed of the computer and in most systems at least keeps the computer fully occupied while drawing is being done. It is in some systems possible to work with a mixture of single point and vector line drawing. This takes advantage of both methods to output graphical data at a maximum speed with a minimum of computer time.

1.2.2 Computer compatibility

The compatibility of the computer to the display is unique for every combination of the two systems being considered. In general, the electronics do not present a technical problem as far as voltages and currents are concerned, since these can usually be matched at very little expense with off-the-shelf components. Rather, the difficulties encountered usually result from the organization of the data port to the computer. If the computer must communicate with the display via a complex set of signals, or if the timing requirements are critical, then it may be very complicated for the display and the computer to communicate with each other. If the computer does not have an efficient method of direct memory access, bandwidth limitations might also be encountered. Finally, the software cannot in some cases be easily modified to cope with peripherals for which the system was not originally designed. These problems can usually be overcome, and minicomputers do not in general present insurmountable interfacing difficulties.

1.3 Selecting the Display

To the viewer, the display should be a black box which quickly presents the data he requests, then erases, adds or modifies parts of this data at his command. The computer is programmed to provide controlling signals and graphical data to the display according to the operator's specifications. These commands may be given directly to the computer but might be given via the display, perhaps by pointing at a position which must then be translated into a coordinate by the display hardware. The display system must then be able to convert the computer information which results from the user's commands into graphic data for the user.

1.3.1 Refreshed image displays

There are two methods by which an image can be created on a display. The first is by drawing the image fifty times or more per second on a non-storing surface. The data for the image must in this case be stored in a memory either in the display system or in the associated computer. The memory may be either analogue or digital and either solid state or electromechanical.[41] Using this method, the facilities available for erasing and manipulating all or parts of the image are a function of the associated memory rather than of the display itself. In the case of digital storage, these functions are usually easy to achieve.

The large screen, high resolution display being investigated here would have about 4×10^8 addressable points. In a raster scan data format, all points on the display must be addressed each time the image is written. The unachievable bandwidth which is implied for such a system rules out the possibility of using a raster scan format.

If a vector or single-point format is used, all points on the display need not be addressed. It is the number of data points, rather than the size of the display, which is limited by the bandwidth. Thus, at reduced data volumes, it is possible to operate a large screen display in a refresh mode. However, for the cartographic application, if only one tenth of one percent of the addressable points were to be displayed simultaneously, then the bandwidth required would be too high to be handled by existing display technologies.

1.3.2 Storage Displays

Since it is not possible to build the required display using a refresh mode technology, the possibilities of storage systems must be considered. The image in this second type of display is created by using a material on which the data need be written only once. The use of this method reduces the bandwidth requirements to a technically achievable value and eliminates the need of an auxiliary memory for the display. It is possible, with any of several existing display technologies, to create an image of the required resolution.

There are two problems which make the use of a stored image display complicated. Firstly, in the process of editing and manipulating data, all or parts of the image must be eventually erased and redrawn. There are very few display devices which can combine both the high resolution and the desired erasure characteristics in one material or system. Selectively erasing parts of the image is the most difficult problem, but this is not a primary requirement of the desired cartographic display, and need not be considered in the initial selection of suitable display technologies. Although the erasure of the entire screen each time the image is to be changed is easier than selective erasure, it too presents many difficulties. The most easily achieved erasure for the entire screen would be the actual replacing of the screen material as is done in photographic projection systems. This method is, however, too expensive to be acceptable.[58] There are a very limited number of other systems which can be erased successfully, or equally as important, be erased many times without suffering severe fatigue.

The second problem with stored image systems is the limited image size. It is not possible with existing technologies to draw an image of the required size and resolution on an erasable medium. Thus, it is necessary to find some method of enlarging a much smaller image. The only known method by which this can be accomplished is optical projection. This in turn presents more complications but is the only possibility presently available for creating a large screen, high resolution system.

1.3.3 Selection of a technology

Based on the information summarized in this chapter, plus the capabilities of different display technologies, as outlined in Appendix Two, a choice was made of the technology which could meet the requirements listed in the Introduction. Immediately non-store systems were ruled out because of the high resolution needed. Laser devices using solid state deflection cannot meet the resolution requirements while galvanometer and voice coil driven mirrors, unless prohibitively expensive, lack the necessary speed and stability. Directly addressed (matrix addressed) displays fall more than an order of magnitude short of being able to provide the resolution needed. Thus, cathode ray addressing provides the only alternative for realizing the required system.

Cathode ray tubes must be used in conjunction with optical projection to obtain the size of display needed. The only cathode ray tube targets which can successfully store an erasable image, and at the same time meet the resolution requirements at a reasonable cost, are made of cathodochromic materials. A diffracting plastics CRT target approaches the minimum resolution requirements, but the literature indicates that fatigue is still a problem with plastics. Finally, the more sophisticated optics system required to project a diffraction pattern rules this out as a first choice for a large screen display.

CHAPTER TWO

PROPERTIES OF CATHODOCHROMIC MATERIALS

In this chapter a brief history of cathodochromic or dark trace materials is given, followed by an outline of the basic concepts of colour centres. The properties which a good cathodochromic CRT screen material must possess are discussed and the most useful materials for this application, KCl and sodalite.Br, are described.

2.1 A History of Dark Trace

2.1.1 Early investigations

Goldstein[129-133] is generally credited with the discovery that certain materials develop absorption bands in the visible light spectrum when bombarded by electrons. His first work appeared in the literature just before the turn of the century, but even in the early 1800's, studies were published concerning the bleaching of naturally coloured rock salt and the reproduction of these colourations by electric sparks, ultraviolet light, and chemical means.

In the 1920's Przibram[142] was attracted to this problem. Over a period of years he and his collaborators produced an extensive series of researches on the colouration of solids.[143] At about the same time other now familiar names also began to appear associated with this phenomenon. These included Frenkel[135] and Schottky.[136,137] A decade later Pohl[148,149] became interested in the conduction of electricity in insulating solids. He was led by these investigations into a study of the colouration of the alkali halides. It was Pohl who coined the term 'colour centre' for certain electronic configurations which, in a solid, lead to optical absorption bands in a normally transparent spectral region.

In 1937 De Boer[150] proposed an electronic model for one of the colour centres in the alkali halides. This is the F centre, which describes an electron trapped at the position of a missing halogen ion in the crystal lattice. De Boer's description has withstood the tests of the most sophisticated experiments and is now generally accepted as correct. Models for several other colour centres were later proposed in extensive works by Seitz[179,183,185] but the validity of some of these has not yet been confirmed.

2.1.2 First display applications

Until the beginning of World War II the interest in the colouration of solids was for the most part academic. The demands of war, however, soon led to practical applications of these properties. Potassium Chloride (KCl) was investigated as a screen material for cathode ray tubes in radar displays. KCl is a cubic crystal which is easy to fabricate and handle. It is cathodochromic in its natural state;thus, it requires no special processing for use as a CRT target material. Radar displays using KCl were investigated simultaneously in England, Germany, the United States, and Russia.[156-178] Much of the development work in England was carried out under the direction of R.W. Sutton at the Admiralty Signals Establishment, Bristol, England. In the United States, research proceeded mainly at M.I.T. The names of Ivey, Leverenz, and Rosenthal were well known in this field both during and after the war.

The radar display developed at that time consisted of a KCl target evaporated onto a mica plate which was then supported inside a cathode ray tube. An electron beam impinging on the KCl produced a dark spot or line which resulted in the term 'dark trace' being applied to these devices. In Germany the word used was 'Skiatron'. The property of darkening in KCl and other materials was called 'tenebrescence' while the screen materials which displayed this effect were known as 'scotophors'.

In some devices, the dark lines written on these screens were viewed directly, while in others the image was projected using reflected light from the CRT screen (opaque projection). This was accomplished by means of a spherical mirror and a Schmidt correcting lens. The image was caused to fade in a controlled length of time, usually several seconds, by heating the KCl with a transparent electrically conductive layer of tin oxide, which was deposited between the KCl and the mica.

These radar displays, unfortunately, had shortcomings which prevented them from being put into widespread operational use. Weak signals tended to fade out too rapidly; this effect was accentuated because the large infrared content of the projection lamps used at that time heated the target. Strong signals, on the other hand, were difficult to erase. These 'burned in' traces could be bleached by further heating of the screen while 'flooding' it with the electron beam for several minutes, but this meant that the display was inoperable during that time.

For several years after the war, no further applications of dark trace materials for cathode ray tubes were reported. However, theoretical work on the mechanisms of colour centres led to a large number of papers being published. Many new centres were discovered, their properties described, and their sources hypothesized. The alkali halides were, and still are, the main objects of study. The majority of the present commercially funded colour centre research is not concerned with producing superior cathodochromic screen materials but is aimed at creating photochromic materials suitable for laser addressed memories. However, much of the knowledge gained from this work is equally applicable to cathodochromic materials.

2.1.3 Improved research techniques

The studies of cathodochromic materials carried out two or more decades ago were based mainly on a heuristic approach. Hypotheses had been proposed for the basic colour centre phenomena, but no certain technique had been developed to test the validity of these models. Doping and the double-doping of alkali halides was attempted with many different materials, but with little ability to predict the effects on the colouring properties or colouring stabilities of the resultant mixtures. Colour centre analysis was later assisted by the powerful new laboratory technique of 'electron spin resonance'. This allowed the measurement of the resonance frequencies of the trapped electrons in a crystal.[186,187] Combining these results with a knowledge of the basic crystal structure and associated electron energies, the orbit or combination of orbits of an electron could be ascertained with a reasonable degree of certainty.

Resonance peaks appear and disappear in all photochromic and cathodochromic materials as they are coloured and bleached. Measurement of the position and intensity of these peaks indicates the type and the density of the colour centres. Any irradiation which colours or bleaches a material can also create, destroy, or change up to a half a dozen or more different centres, some irreversibly. As a result of this, the analysis of an individual centre becomes very difficult.

There are other methods of analysis which have been developed to determine the structure of colour centres. Electron double spin resonance, an extension of electron spin resonance, provides additional useful information about the orbits and energies of electrons in colour centres. Measurements of the polarization and directional intensity of emitted radiation when colour centres are bleached, can detect a lack of colour centre symmetry within the crystal and also can provide clues relative to the structure of nonsymmetrical centres. The sensitivity to bleaching by polarized light can be measured and also will detect the presence of centres which are not symmetrical. Further information can be obtained by studying the changes in the colour centre properties as a function of temperature.[99]

2.1.4 Investigations of sodalites

A large part of the published literature describes research into the properties of the alkali halides. There are, however, other groups of materials which are known for their properties of colouring under radiation, the most significant for cathode ray tube targets being the sodalite group. These materials are aluminosilicates and include the minerals sodalite, noselite, hauynite, lazurite, ultramarine, genthelvite, danalite, and helvite. Sodalite is frequently found in its natural state with a blue, pink, or green colour. This colouration generally bleaches under sunlight, and this is often an irreversible process. Such descriptions appear in the literature as early as 1901.[138-141,144,187-190]

The three sodalites which have been studied for display applications are sodium aluminum silicates which have the formula $3(Na_2O.Al_2O_3.2SiO_2).2NaX$, where X can be Chlorine, Iodine, or Bromine. The crystal structure is built up from cubo-octahedral cages of (AlO_4) and (SiO_4) groups. The cages are stacked together to form a crystal with overall cubic symmetry. There are $(Na_4X)^{3+}$ groups located inside each cage. The cathodochromic properties of these materials are the result of electrons being trapped in vacancies where a Cl, Br, or I ion would normally be found.

Medved was the first person to synthesize sodalite.Cl in 1953.[191,192] Kirk's report quickly followed describing another process.[193,194] Other papers have since described the fabrication of all three cathodochromic sodalites and also attempts to make them more sensitive to colouration or erasure by variations in manufacture and by changes in doping.[195-203] Because of its more complicated crystal structure, there is less certainty of the exact structure of the colour centres created during irradiation [204-206] and whether doping, particularly sulphur, is involved in this process.

A large amount of practical work has been carried out in the application of the sodalites to cathode ray tube displays because of their excellent properties. These include the ability to control their image storage properties by variations in the material composition, doping, and fabrication. They also exhibit good immunity to burning under high intensity electron beams which evaporate KCl. Following Ivey's patent in 1956,[207] the Royal Radar Establishment at Malvern in England was the first [208,209] of many to study these materials for cathode ray tube applications.[220-222] Subsequently, the work was continued for a time at Ferranti in England. Actively involved at the present time are the RCA laboratories in Princeton, New Jersey.[210-219] A sodalite screen display is now being manufactured by Optel.*

2.1.5 Other cathodochromic materials

Other materials have been studied for their colour centre properties but appear to be less applicable to cathode ray tubes. These include calcium titanate,[211,212] titanium dioxide,[234] magnesium oxide[233] the silver halides,[235] strontium titanate,[224] the alkaline earth fluorides,[211,226-232] many other minerals,[235] and several organic materials. A great interest has also been shown in colour centres in doped quartz.[236-239] The materials listed above suffer from either exhibiting low contrast or rapid bleaching in light, or requiring excessive energies to produce colouration. It is possible that some of these, particularly quartz, will prove useful as more knowledge of the physics of these materials is gained and can be applied to modification of their properties.

2.2 Colour Centres

The basic theory of colour centres is comprehensively summarized in the book by Schulman and Compton [171];548 references are included. Only a brief outline of colour centres is given in this section to explain the problems of colouring, bleaching, and fatigue which occur in cathodochromic materials. The basic concepts are discussed mainly with reference to the alkali halides since these materials are the most extensively researched and documented, and because their crystal structure is less complex than that of most other cathodochromic materials.

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* 'Optel Reflicon Display Model D-10', Optel Corporation, Box 2215, Princeton, New Jersey 08540.

2.2.1 Crystal defects

The existence and properties of colour centres result directly from the presence of defects in a crystal lattice. Thus, a description of the origin and properties of the defects involved in colour centre phenomena must first be presented. In any ionic crystal, no matter how carefully grown, there will be defects if the crystal temperature is above absolute zero. It can be shown that for an ionic crystal to be in thermodynamic equilibrium, that is, to have its entropy at a maximum, a definite number of defects must exist at any given temperature. These thermally generated defect vacancies might be Frenkel defects (figure 2.1) which result from either cations or anions being displaced to interstitial sites. Alternatively, they might be cation and anion vacancies, termed Schottky defects (figure 2.2).

The defects which require the least energy to be generated will normally predominate in any crystal. This is a function of properties of the crystal such as temperature and ion size. At room temperature, for example, the silver halides contain mostly Frenkel defects while the alkali halides have a majority of Schottky defects. However, thermodynamic equilibrium does not exist in some processes which generate colour centres and other defects may be created by high energy radiation. Thus, the properties of a material cannot always be predicted solely on the basis of the equilibrium defects expected in the crystal.

Impurities in a crystal can be a source of vacancy defects or interstitial atoms. Figure 2.3 gives three examples of this effect. In a monovalent ion crystal a divalent cation has been in each case substituted at one lattice site. This introduces an extra positive charge to the crystal. In order to preserve electrical neutrality, a vacant cation site can be formed in the lattice. Alternatively, an interstitial negative

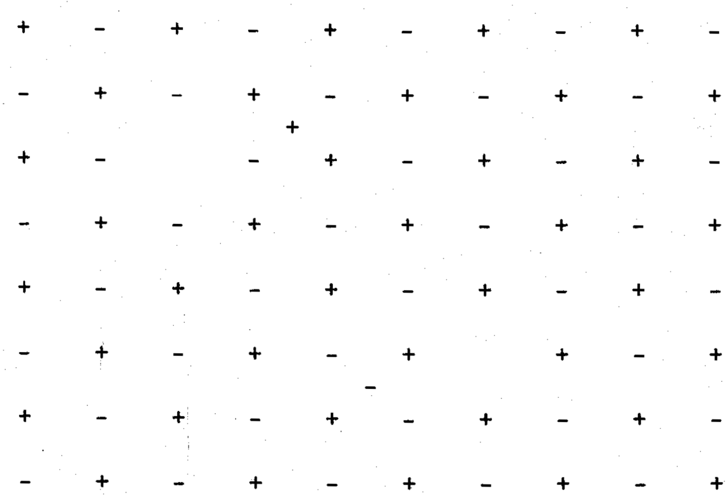

Figure 2.1 Frenkel defects.

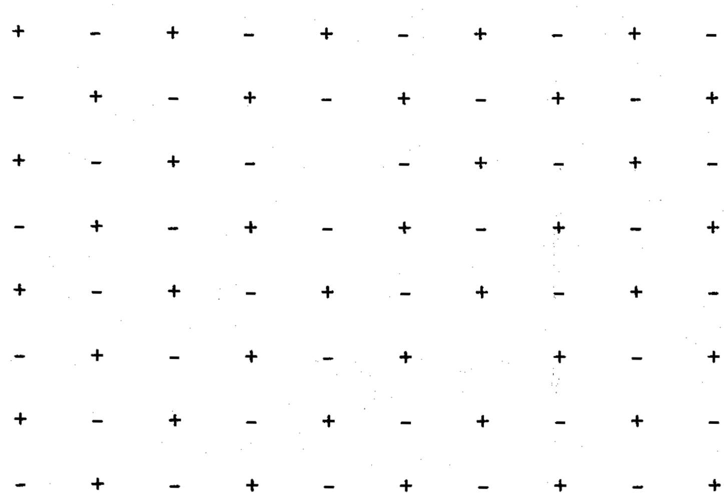

Figure 2.2 Schottky defects.

ion could be incorporated into the crystal. Finally, by introducing a second impurity which provides divalent anions, interstitial ions and vacancies could be avoided; and instead, oppositely charged ion pairs could be found in nearby lattice sites. Figure 2.4 illustrates other more intricate defects which can exist in a crystal. These include vacancy pairs and ion vacancy complexes.

Many of the properties of colouring, bleaching, and fatigue exhibited by cathodochromic crystals are dependant upon the migration of defects through the crystal lattice. Neutral entities such as shown in figure 2.4 may move through the crystal because of thermal agitation at elevated temperatures or due to kinetic energy introduced by radiation. These defects may become trapped, forming colour centres or they may annihilate one another, causing bleaching. However, certain types of defects may group together to form more complicated defect complexes which, if they cannot be destroyed, result in fatigue.

There exists a wide range of defect types and defect interactions which are possible in a crystal. Two further types not discussed above are edge and screw dislocations. These usually do not play major roles in the colour centre properties of crystals,except occasionally to act as collecting points for some of the complex defects which might be formed.

2.2.2 Defects as colour centre traps

If a crystal is irradiated, for example by X-rays, electrons are stripped from ions in the crystal. This creates an equal number of free electrons and holes, most of which quickly recombine. A few electrons, however, will wander near interstitial cations, anion vacancies or other

```
-     +     -     +     -     +     -     +     -     +     -     +

+     -     +     -     ++    -     +     -     +     -     +     -

-     +     -     +     -     +     -     +     -     +     -     +

+     -     +     -           -     +     -     +     -     +     -

-     +     -     +     -     +     -     +     -     ++    -     +
                                       -
+     -     +     -     +     -     +     -     +     -     +     -

-     +     -     +     -     +     -     +     -     +     -     +

+     -     +     -     ++    -     +     -     +     -     +     -

-     +     -     +     -     +     --    +     -     +     -     +

+     -     +     -     +     -     +     -     +     -     +     -
```

Figure 2.3 Examples of impurity induced crystal defects.

```
+     -     +     -     +     -     +     -     +     -

-     +     -     +     -     +     -     ++    -     +

+     -     +     -     +     -           -     +     -

-     +     -     +     -     +     -     +     -     +

+     -     +     -     +     -     +     --    +     -

-                 +     -     +     -     +           +

+     -     +     -     +     -     +     -     +     -
```

Figure 2.4 Examples of multiple vacancy defects in a crystal.

positively charged defects and become trapped by coulomb forces. In the same way, some positive holes will wander until they become trapped at negatively charged defect sites. As explained earlier, these trapped electron and hole sites are termed colour centres and affect the optical properties of the crystal by absorbing light of a frequency which is dependant upon the type of defect involved.

The trapped electron or hole centres can be destroyed (bleached) by heating the crystal or irradiating it with light of an appropriate wavelength. Either action raises the energy of the electrons or holes to a condition where they are freed and can wander through the lattice. Eventually these oppositely charged ions will encounter each other and be annihilated. For the alkali halides and sodalites, in most cases, the mobility of the electrons is much higher than that of the holes and bleaching can be considered as due to the freeing of trapped electrons.

Bleaching of one colour centre can produce one or several other centres in a reversible or irreversible manner. This effect may be due to migration of colour centres, or retrapping of electrons or holes by other centres, or both. Some centres may be created only at low or at high temperatures. There can also be interaction between colour centres in close proximity within a crystal. This will modify the absorption properties of the centres involved. Thus, a vast range of interaction is occurring in a colour centre system and accurate analysis of individual colour centre properties is usually very difficult.

This analysis is further complicated by trace impurities which are always present even in the most pure materials available. Trace impurities have only recently been recognized in the alkali halides as playing a major role in colour centres, which were previously thought to exhibit properties resulting from the pure material. Impurities can cause absorption bands to be shifted and broadened by a change in lattice constant if the impurity ion size is different from that of the crystal. Ions with a different valence can create new centres or change the colouring and bleaching properties of existing centres. The maximum density of a colour centre may be increased or decreased. The effects of different impurities are well documented for the alkali halides and to a lesser extent for other materials exhibiting colour centre absorption.

2.2.3 Trapped electron absorption bands

2.2.3.1 F centres

Each type of colour centre absorbs light of a specific wavelength causing what is termed an 'absorption band' to be generated. The nomenclature used to designate the absorption bands has been made arbitrarily by the discoverers. However, once a name is applied to a colour centre produced by one defect type, the same name is logically applied to this defect in another cystal, even if the absorption band falls at a different place in the optical spectrum. In general the longer wavelength absorption bands such as the L, F, and K bands (see Table 2.1) are the result of trapped electrons while the shorter wavelength V bands are produced by trapped holes.

The centres which are of current interest in the study of the alkali halides and sodalites for display applications are the F centres, because

Center	L_3	L_2	L_1	K	F	F'	F'	R_1	R_2	M	α	β	H	V_1	V_k	V_2	V_3	V_4
Temperature of observation (^oK)	93	93	93	93	300	140	170	300	300	300	~90	~90	4	77	77	300	300	90
LiF					250			313	380	444					348			
LiCl					385				580	650								
NaF					341				415	505	131	127						
NaCl					458	510		545	596	725	174	168	330	345		223	210	
NaBr					540						199							
Na I					588													
KF					455				570									
KCl	251	288	344	457	556		750	658	727	825	177	166	335	356	365	230	212	~254
KBr	276	316	374	525	625		700	735	790	918	201	192	380	410	385	265	231	275
K I	326	382	447	585	689						238	226			404			
RbCl	279	335	402	523	609													
RbBr	300	362	435	593	694			805	859	957	205	196						
Rb I	338	413	506	646	756						240	229						
CsCl					605													
CsBr					680													

Table 2.1. Wavelengths of the Absorption Peaks Arising from Various Trapped-electron and Trapped-hole Centers in the Alkali Halides (mμ) (from Shulman & Compton)

they form the most intense absorption band in the visible portion of the spectrum. The F band is a bell-shaped absorption band of which the centre frequency for the alkali halides of the sodium chloride structure has been derived empirically by Ivey[181] as:

$$\lambda_{max}(\text{in Å}) = 703\ d^{1.84}$$

where d is the lattice constant in Å. This also holds true for solid solutions of these salts. The centre frequency shifts to longer wavelengths as the temperature of the crystal is increased. At the same time, the band broadens and flattens.

The F centre in the alkali halides has been conclusively shown to be an electron trapped at an anion vacancy in the crystal. The existence of the electron in this position causes a shift in the position of surrounding ions, with the positive ions moving closer to the electron and the negative ions moving farther away. The potential well in which the electron finds itself has several discrete energy levels; hence, the absorption of energy at a suitable wavelength can raise the energy level of the electron in the well.[153-155] As an example, the energy required to raise an electron to the first higher excitation (1s-2p) level is found experimentally to be 2.72 e.v. in sodium chloride. This transition is the source of the F absorption band and results from the absorption of a photon of light in the blue part of the visible spectrum.

After a short period of time, which is the lifetime of the electron in its excited state, about 10^{-6} to 10^{-8} seconds, the electron will fall back to its ground state, with the emission of energy which may be either in the form of a photon of longer wavelength (Stokes shift) than the exciting energy, or in a radiationless form of heat (lattice vibrations). The probability of radiation being emitted when the electron falls back to the ground state can be affected by impurities and complex colour centres which may exist in the crystal.

Any trapped electron can receive sufficient energy from the thermal motion of the lattice to raise it to the conduction band,and thus, free it from the trap. This is one mechanism by which colour centres are bleached. At higher temperatures bleaching is quite rapid while at room temperature it is so slow for many of the alkali halides and some sodalites, that the colour centres survive for months if maintained in the dark. If F band light is being absorbed by the colour centres, then there is a finite period of time during which they are in an excited state. The energy required to lift these electrons from their excited state to the conduction band is less than that required to lift them from the ground state to the conduction band at any given temperature. Thus, thermal bleaching will occur more rapidly if the crystal is exposed to F band light. This phenomenon is not unique to the F band, but applies to some extent to all the absorption bands.

2.2.3.2 other trapped electron centres

The F absorption band has been found to exist simultaneously with four other weaker bands of shorter wavelengths in the alkali halides. These are the L_1, L_2, L_3, and K bands. Some of these escaped notice in early investigations since they fall within the F band and appear only as small irregularities on its short wavelength side. These bands and their wavelengths are listed in Table 2.1 for the materials in which they were investigated. The K band is due to a high excited state of an electron at an F centre trap.

The L bands are also due to the same defect site, but it is not definite whether they represent still higher energy levels of the trapped electron or whether they occur when an electron is freed to the conduction band. Two other bands, the α and β bands, are also directly attributed to the same centre. However, it is felt that these are due to a perturbation of the fundamental lattice absorption of the crystal by the presence of the F centre, rather than to a transition of the F centre itself.

The F' band is generated on the long wavelength side of the F band when a crystal containing F centres is bleached at low temperatures by F band light. The F' band is thermally unstable and disappears as the temperature of the crystal is raised towards room temperature. This results in the regeneration of the F band. The F' band results from an anion vacancy which has trapped two rather than one electrons. The second electron is much less tightly bound than the first and is quickly ejected from the site as the crystal temperature is raised.

The colour centres mentioned to this point are all associated with a single anion vacancy. The F band absorption with its associated L and K bands appears when a crystal is irradiated at ambient and lower temperatures. This produces the darkening in the visible spectrum which is of interest in the applications of the alkali halides for display purposes. Although the α and β bands are directly associated with the F centre, they are outside the visible spectrum and do not represent either a problem or an advantage for display applications.

Unfortunately, the annihilation of the F band by bleaching with F band light at room temperature does not necessarily return the crystal to its original state. Instead, new centres are formed, some of which exist in the visible spectrum. These new centres gradually increase in number during repeated colouring and bleaching of the material and represent one of the sources of fatigue in many cathodochromic materials when used in optical erase mode displays. The centres formed by the optical bleaching of the alkali halides are the M, R_1, R_2, N, and O centres. There is very little data available on the N and O bands, which are the longest wavelength bands discovered in the alkali halides and are outside the visible spectrum.

Upon bleaching of the F band, the M band is the first to appear. It is not possible to create the M band by itself, as it is either present along with the F band, or with the R, N, and O bands if further bleaching occurs. Similarly the R, N, and O bands cannot be prepared without other bands being present, making investigation of the properties and structure of these bands very difficult. The models for these centres, therefore, are quite uncertain and conjectural. It is known now that the M and R centres are non-symmetrical defects involving more than one ion vacancy and with at least one, but possibly two, electrons trapped at the defect site. It has also been argued convincingly that the R_1 and R_2 centres may be different excited states of the same defect configuration.

Recent studies suggest that the M centre is formed by two F centres migrating to adjacent lattice sites while the R centre is an aggregate of three F centres (see section 2.2.5) and the N centre consists of four F centres. At high temperatures, around 100 to 130^{o}C, these aggregates of vacancies apparently are dispersed, leaving the original single anion vacancy defects. In order to explain the generation of these new bands upon bleaching, the concept of trapped hole centres must be introduced.

2.2.4 Trapped hole absorption bands

Trapped hole centres are generated at the same time as trapped electron centres during irradiation of a crystal. They have no direct effect on the visible properties of the crystal,since the absorption bands generated are in the ultraviolet region of the spectrum. Some hole centres, however, cannot be ignored since they have a direct influence on the F centre bleaching, as is described in section 2.2.5. The centres of interest are interstitial anions which have trapped holes. These can also be thought of as interstitial halogen atoms. They are called H centres and are listed in Table 2.1 for some materials. Other trapped hole centres will not be discussed here, other than to say that, in most cases, they do not have configurations which can be considered analogues of the trapped electron centres.

2.2.5 F centre aggregation

It was stated that room temperature bleaching of F centres generated new absorption bands, the M, R, N, and O bands by the mechanism of F centre aggregation. Recently, further bands have also been found to result from F band bleaching. These are apparently yet more complex aggregations of F centres which further contribute to the problem of fatigue when using these materials for display applications. Redman and Tubbs[240] investigated this phenomenon in electron irradiated potassium bromide at room temperature and at liquid nitrogen temperature. They found that room temperature irradiated crystals formed these new bands upon bleaching with a helium-neon laser. Crystals irradiated at liquid nitrogen temperature did not yield these new bands regardless of whether bleaching occurred at liquid nitrogen or room temperature, indicating that the difference in bleaching properties was the result of irradiation at different temperatures. They further found that upon irradiation at either temperature, a large ultraviolet absorption band, which corresponded to trapped hole centres, (in this case H centres) was formed as expected. Bleaching of the liquid nitrogen temperature irradiated crystal, destroyed the ultraviolet H centre absorption band, but bleaching of the room temperature irradiated crystal had no effect on the intensity of the H band abosrption, indicating that in the former case recombination of interstitial atoms and vacancies was the bleaching mechanism while in the latter case bleaching occurred by F centre aggregation.

High energy electron irradiation is known to generate a large number of anion vacancy and interstitial anion pairs by knocking ions from the lattice into interstitial sites. The number of anion vacancies created is far above the thermodynamic equilibrium value. Redman and Tubbs suggest that at room temperature these interstitial halogen atoms have sufficient mobility to migrate into pairs or groups which are stable under F band light and thus, do not take part in the bleaching process. When irradiation occurs at liquid nitrogen temperature, the mobility of the anions is low enough so that they remain as individual atoms near their original lattice sites. Bleaching causes them to return to their lattice locations, forming again a perfect crystal at that point.

The importance of this process at room temperature is its irreversibility, which is described in cathode ray tube applications as fatigue. The halogen atoms, or H centres, gradually form larger clusters under repeated irradiation and bleaching. The excess alkali ions which result, collect in the spaces created by F centre aggregates, or in spaces created by screw and edge dislocations, to form colloids that change the absorption properties of the crystal by creating a permanent visible absorption band called the X band.[241] It is not certain if these colloids are formed when thermal bleaching is used. Some literature suggests they are, but at a much slower rate than with optical bleaching. This is supported by the observed permanent darkening of commercial potassium chloride CRT targets screens after extended use. When colloids do exist in the alkali halides, they can be dispersed by heating the crystal to about 600°C; however, this cannot be done in a practical cathode ray tube. There is no published evidence of colloid formation in the sodalites.

2.3 Cathodochromic Materials for Display Applications

There are four general properties which must be considered in the selection of a cathodochromic material for display applications. These are:

1. image storage stability,
2. writing sensitivity,
3. image contrast, and
4. material stability.

These properties are here described only for the materials KCl and sodalite. Br. Although no other presently researched materials can meet the requirements necessary for the cathode ray tube display required, some will be mentioned in order to indicate the reasons for their unsuitability.

2.3.1 Image storage stability

The most difficult requirement to achieve for a target material is image storage stability. The image must not fade rapidly under the intense light required for a large projected image. According to the literature, the only material which can meet this requirement and also has the necessary writing sensitivity and contrast is sodalite.Br. Images written on KCl were reported to fade rapidly under strong light.[215] However, early experiments described in this thesis indicated that this was not always the case and so prompted further investigations of KCl as a CRT target material.

Most cathodochromic materials, including KCl and the three sodalites (sodalite.Br, sodalite.Cl, and sodalite.I) exhibit F band colouring in two stages under electron beam irradiation. The first stage is described as the optical mode,since the absorption band can be bleached by light at room temperature. Further irradiation produces colouration which can only be bleached with heat. This is known as thermal mode colouration. No explanation for the two modes of colouring has been found in the literature. It would seem likely that optical mode colouring results from electrons trapped in existing vacancies while thermal mode colouring is due to traps created by electrons generating interstitial anion and vacancy pairs. This would seem plausible since, as mentioned previously, F band light does not always cause these interstitial anions to recombine with the vacancies.

Sodalite.I exhibits a large optical mode colouration and is almost totally bleached by F band light,while KCl and sodalite.Cl show moderate thermal mode colouring. Sodalite.Br colours almost totally in the thermal mode. Thus, it exhibits the most suitable image retention properties for use in displays which employ optical projection systems.

2.3.2 Sensitivity

Another important property of a cathodochromic material is its sensitivity. This describes the amount of colouration which is produced per unit of charge deposited on the material by the electron gun at a specified acceleration voltage. The practical limit to acceleration voltage for a normal display CRT is about 30 KV. Above this value, X-ray shielding becomes critical and deflection sensitivity of the electron beam drops to a value which is difficult to handle with commercially available deflection systems. Commercial and experimental cathodochromic CRT's to date have generally been operated at accelerating voltages of up to 28 KV.

The sensitivity to colouration has only been documented in quantitative terms for very few materials. These measurements have all been made on powders allowed to settle onto a flat surface, or on flat evaporated polycrystalline targets. The quantity of charge described as necessary to produce a barely visible line on KCl varies by three orders of magnitude depending upon the source quoted.[242-244] However, for display purposes this is less important than the charge needed to produce a high contrast line suitable for projection. KCl and the three sodalites have similar sensitivities with approximately 10^{-8} coulombs per square millimeter (C/mm.^{2}) at 20 KV producing contrast ratios of 2 to 1, and 10^{-7} C/mm.^{2} yielding contrast ratios as high as 10 to 1 for the same acceleration voltage.[211,213,245]

A more convenient method of listing sensitivity for display work is by the number of points per second which can be drawn at a specified contrast ratio and beam current. For sodalite.Br or sodalite.Cl, Taylor et al.[209]

find a writing rate of 10^4 points per second at a contrast ratio of 3 to 1, accelerating voltage of 20 KV and beam current density of 0.47 amperes per $cm.^2$ Heyman et al.[215] find a higher contrast ratio of 7 to 1 at the same writing speed and accelerating voltage, but claim a beam current of 20 micro-amperes per square inch (1.3×10^{-4} amperes per $cm.^2$). However, this figure is in apparent disagreement with other data in the same paper by about four orders of magnitude and probably represents a typographical error. By increasing the accelerating voltage to 30 KV it is possible to improve on this writing speed to some extent, but the limited beam current capability of high resolution electron guns permits further increases in writing speed only if contrast is sacrificed. About 2×10^4 points per second is the maximum that can be achieved at reasonable contrast ratios.

Other materials which have been studied but are not sensitive enough for cathode ray tube applications include NaCl, quartz, and $CaTiO_3$.

2.3.3 Contrast

The image contrast is dependant upon the maximum absorption band intensity which can be generated. All cathodochromic substances reach saturation levels beyond which no more colour centres can be generated. This can be a function of temperature, doping, and other properties of the material. $CaTiO_3$ is an example of a material which saturates at a contrast ratio of about 2.3 to 1 at room temperature. The contrast ratios of settled powder or evaporated targets of KCl or sodalite.Br can exceed 100 to 1 under intense irradiation.

The position and shape of the optical absorption band in the visible spectrum is also of importance in determining the apparent contrast of an image. The eye has a response curve (figure 2.5) which is most sensitive to

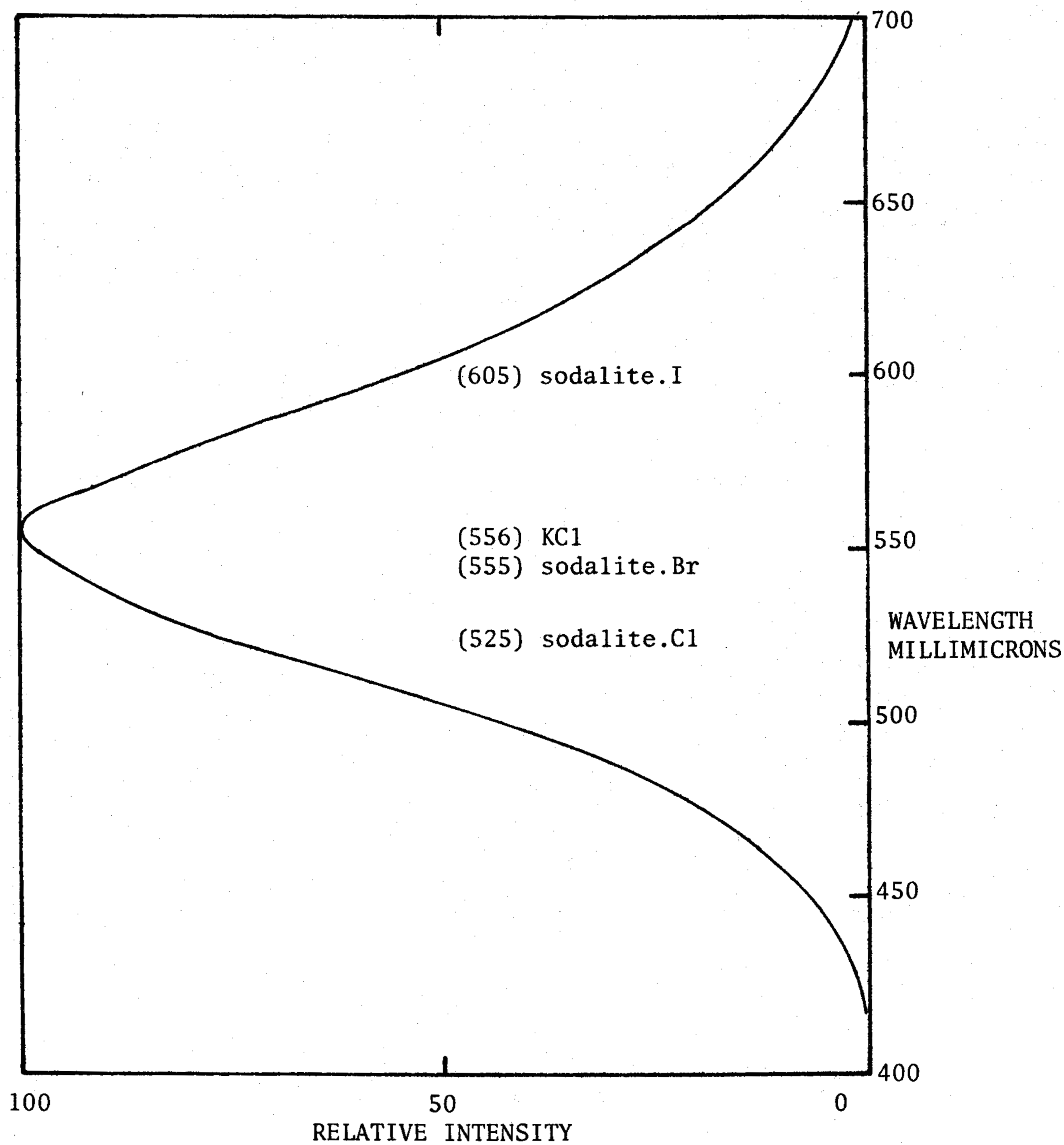

Figure 2.5 Spectral Absorption of KCl and the sodalites.

light in the green part of the optical spectrum. An absorption band at this frequency will appear much darker to the eye than one of the same intensity near either end of the visible spectrum. Figure 2.5 also shows the F centre absorption bands for KCl and sodalite.Br. For both of these materials, the absorption band falls very near to the centre of the spectrum. The apparent colour of the absorption band is magenta under white light or black under green light. A wider absorption band would be ideal as it would appear black under white light, but, in fact, the magenta line is adequate for display purposes.

2.3.4 Material stability

The final test of viability for a CRT target material is whether it can survive several thousand hours of use without severe deterioration. One problem which is prevalent with KCl targets in usage is their susceptibility to burning, if the electron beam remains stationary. The heat generated literally evaporates the KCl from the CRT target. Sodalite.Br is reported to be much less sensitive to burning than KCl.

Another aspect of material stability is the problem of fatigue. This has prevented the use of any organic materials for erasable targets since they break down after only a few hundred write and erase cycles. The alkali halides are acceptable in a thermal erase mode. There is no documented evidence of fatigue occurring in the sodalites when they are operated in the thermal erase mode.

2.3.5 Comparison of KCl and sodalite.Br

The properties of KCl and sodalite.Br which are of importance in cathodochromic applications are summarized in Table 2.2. The better CRT target material for the cartographic display is sodalite.Br, primarily on the basis of its superior image retention properties in the presence of high intensity F band light (see, however, section 4.2). Its slightly broader absorption band, less sensitivity to electron beam burning, and reported immunity to fatigue are also advantageous. They are not, however, compelling reasons for preferring sodalite.Br to KCl, since KCl, through years of use in commercial devices, proved itself acceptable in these respects.

In terms of colouring properties, sodalite.Br has no advantages over KCl. The sensitivity to colouration and the highest contrast attainable are, for these two materials, identical. The maximum colour centre density which can be produced (either measured or theoretical) is also the same, indicating that for practical purposes, colouring properties observed in one material could be considered as valid for the other.

KCl has the advantages of being inexpensive, easy to obtain, and cathodochromic in its natural state. It can be fabricated in a transparent, powdered, or evaporated form. Thus, particularly for much of the experimental research, KCl was more practical than sodalite.Br to use.

The fabrication of sodalite.Br is a complicated process requiring special laboratory equipment. The material is grown as small crystals, in a process employing very high temperature and pressure. Doping materials are added during this fabrication process. Following the preparation phase, the sodalite.Br is ground into the proper sized powder for settling onto the CRT target. It is then passed through a sensitizing phase consisting of heating in a hydrogen atmosphere. Once sensitized, sodalite.Br cannot be further

PROPERTY	SODALITE.BR	KCL
Optimal material	Doped with S or Fe	Pure
Sensitivity	High (30% quantum efficiency initially)	Same as sodalite.Br
Maximum contrast ratio	Greater than 30:1	Same as sodalite.Br
Maximum absorption coefficient	$k = 4000\ cm^{-1}$	Same as sodalite.Br
Maximum number of switched centers (from Smakula's eq.)	$2 \times 10^{19}/cm.^3$	Same as sodalite.Br
Lifetime	Months to years	Days to weeks
Effect of strong light	None	Slow bleaching
Resistance to burning	Excellent	Fair
Fatigue	Probably none	Complex centres form slowly (months to years)
Material cost	$10/gram	$5/kilogram

Table 2.2 Comparison of the properties of Sodalite.Br and KCl.

ground without destroying its cathodochromic properties. Thus, with presently known techniques, it is only possible to prepare powdered targets.

Although sodalite.Br exhibits properties which are desirable for the final version of the cartographic CRT, all published experimental evidence indicates that any properties of colouration observed for KCl in a powdered or evaporated form are equally as applicable to sodalite.Br. Thus, it is advantageous to use the much more readily available and easily handled KCl in initial experimental studies of a display for cartographic applications. This does not, of course, preclude the need to prove the validity of sodalite.Br in a final prototype system.

CHAPTER THREE

THE PROPOSED APPLICATION SYSTEM

A block diagram of the proposed system design is shown in figure 3.1. The display employs a conventional cathode ray tube with magnetic deflection to write a high resolution image on a cathodochromic target. This image is optically magnified, and imaged onto a 'rear projection' viewing screen. Thermal erasure of the image is achieved by resistive heating of a conducting layer of indium tin oxide deposited beneath the cathodochromic material.

The design of each subsystem is considered, and its influence on the system design is discussed. The anticipated performance of the prototype display is analysed. Finally, proposals for modifications and improvements to the display are presented which might be achieved as the result of further research and development.

3.1 Computer Interface to the Display.

An interface has been designed which will enable the operation of the display with a minimum of hardware. Software modifications would also be minor to enable the use of the display with any system capable of driving either 'point-mode' displays or mechanical plotters.

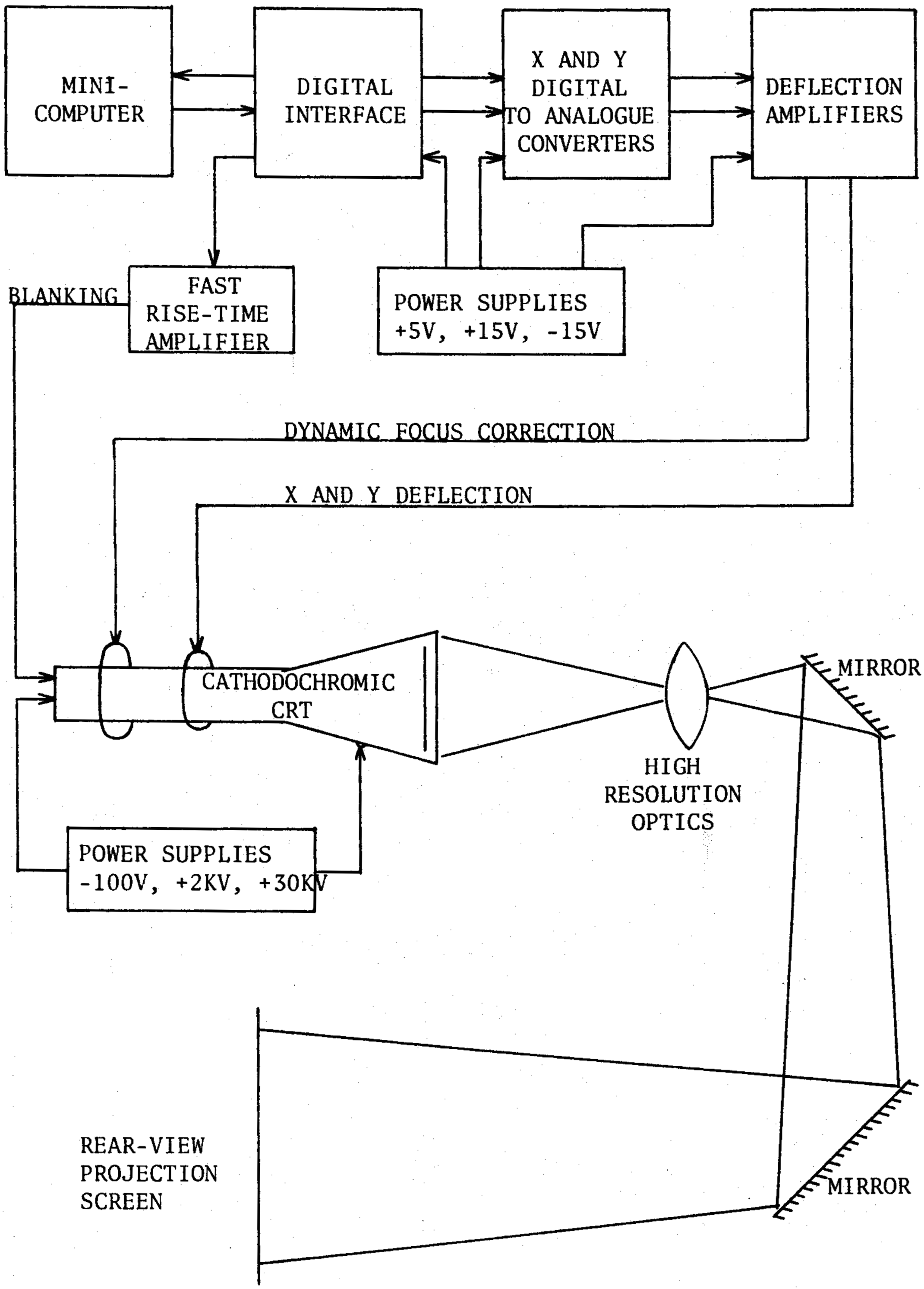

Figure 3.1 High Resolution Display

A functional diagram of the computer interface is shown in figure 3.2. The transfer of data from the computer to the interface is achieved by means of programmed (as opposed to Direct Memory Access) instructions. Absolute coordinates are output directly, while data stored in incremental form can be added to registers in the interface. Circuitry in the interface automatically holds the CRT writing beam on for the required time to write each output image point.

A more sophisticated interface, incorporating Direct Memory Access, data formatting, and hardware vector generator, would be advantageous in a production system (see figure 3.3). This could best be accomplished with the aid of a microprocessor-based controller in order that data formats and computer interfacing details could be easily modified for compatibility with a variety of computer and software configurations.

3.2 Deflection System

3.2.1 Digital to analogue converters

Analogue input signals to the CRT deflection amplifiers are generated by transferring digital coordinate information to high resolution digital to analogue converters (DAC's). The absolute accuracy and linearity of the DAC's are not critical; deviations of several percent can be tolerated. Differential accuracy is, however, essential to the generation of an image with acceptable cosmetic quality.

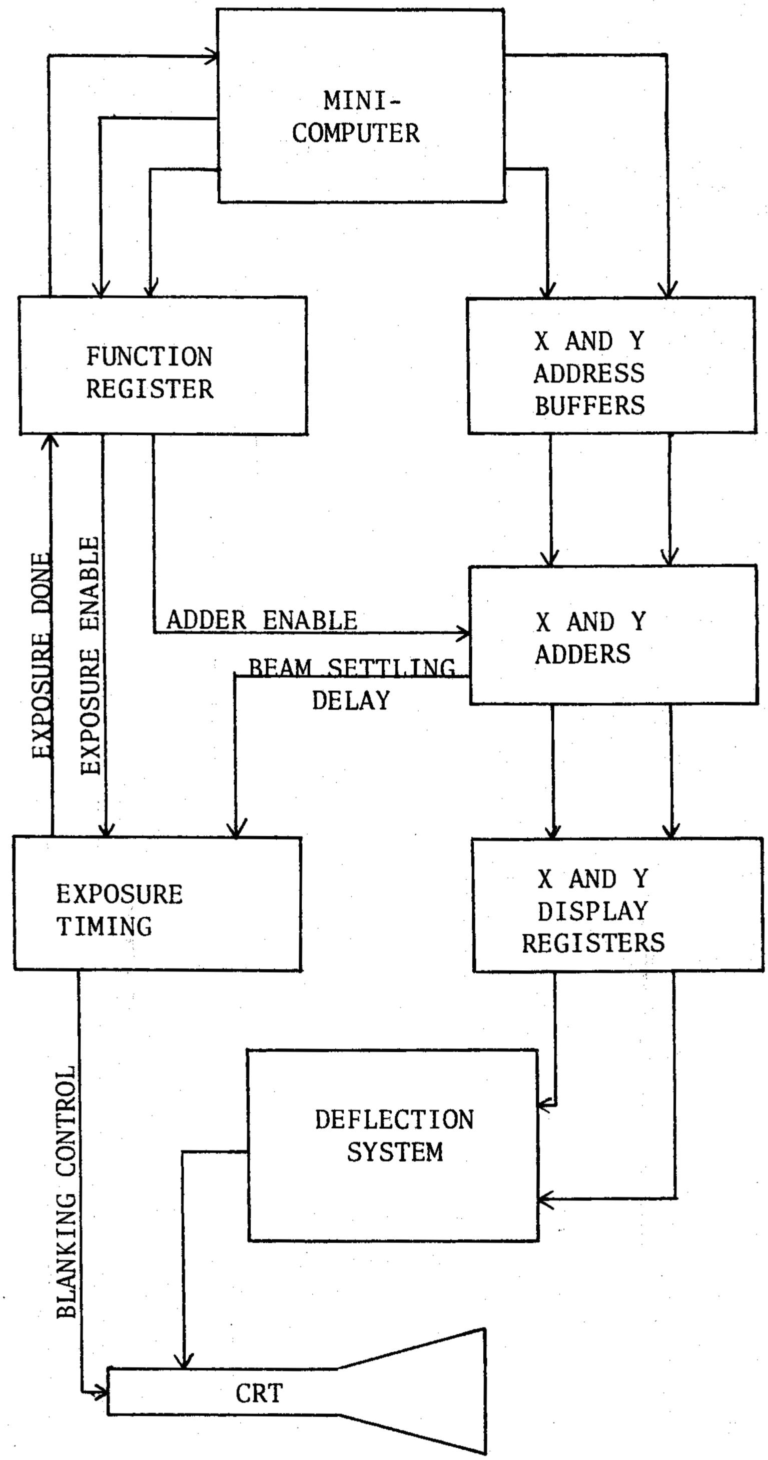

Figure 3.2 Display Interface

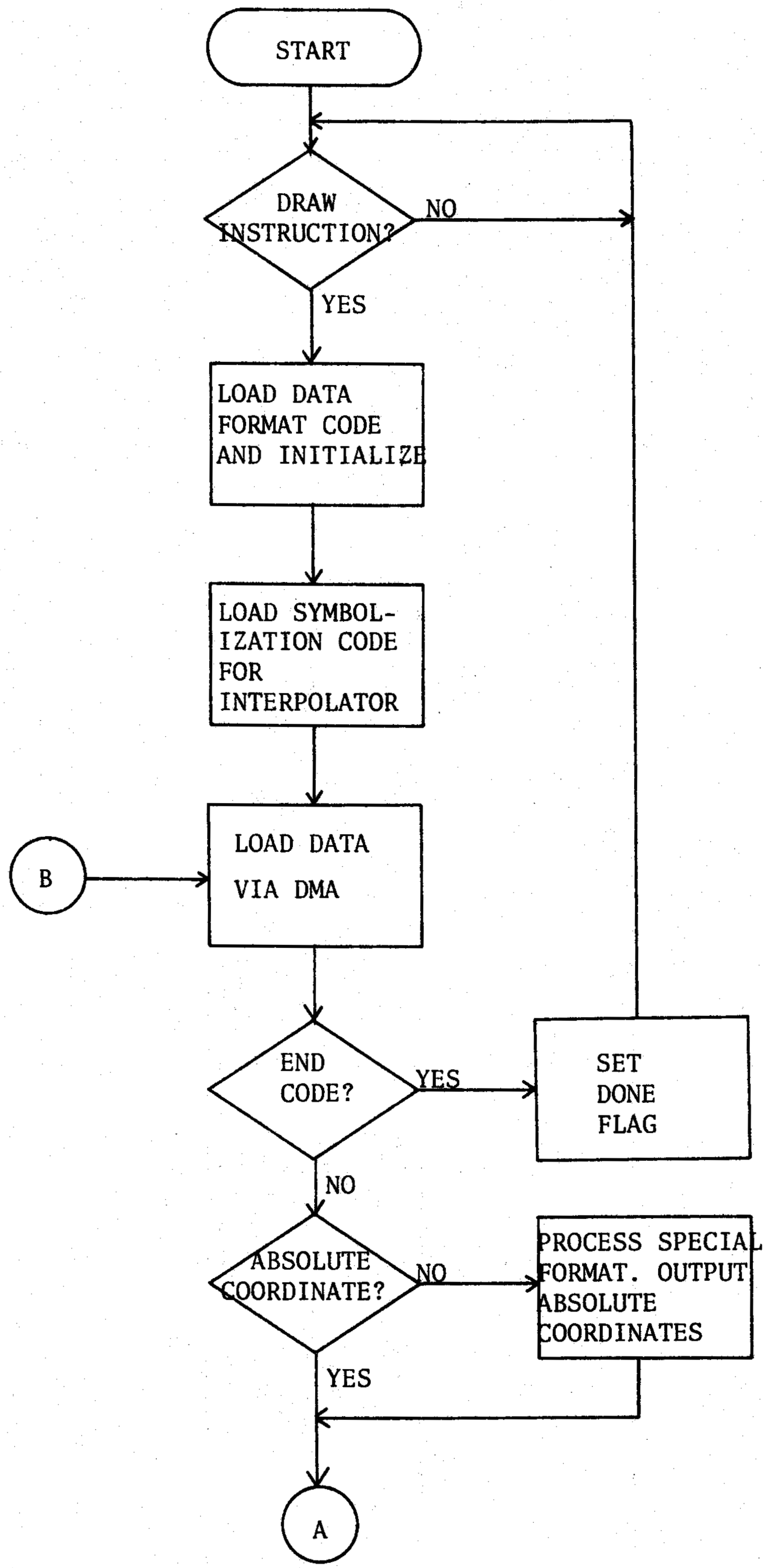

Figure 3.3 Flowchart of DMA Interface with microprocessor control.

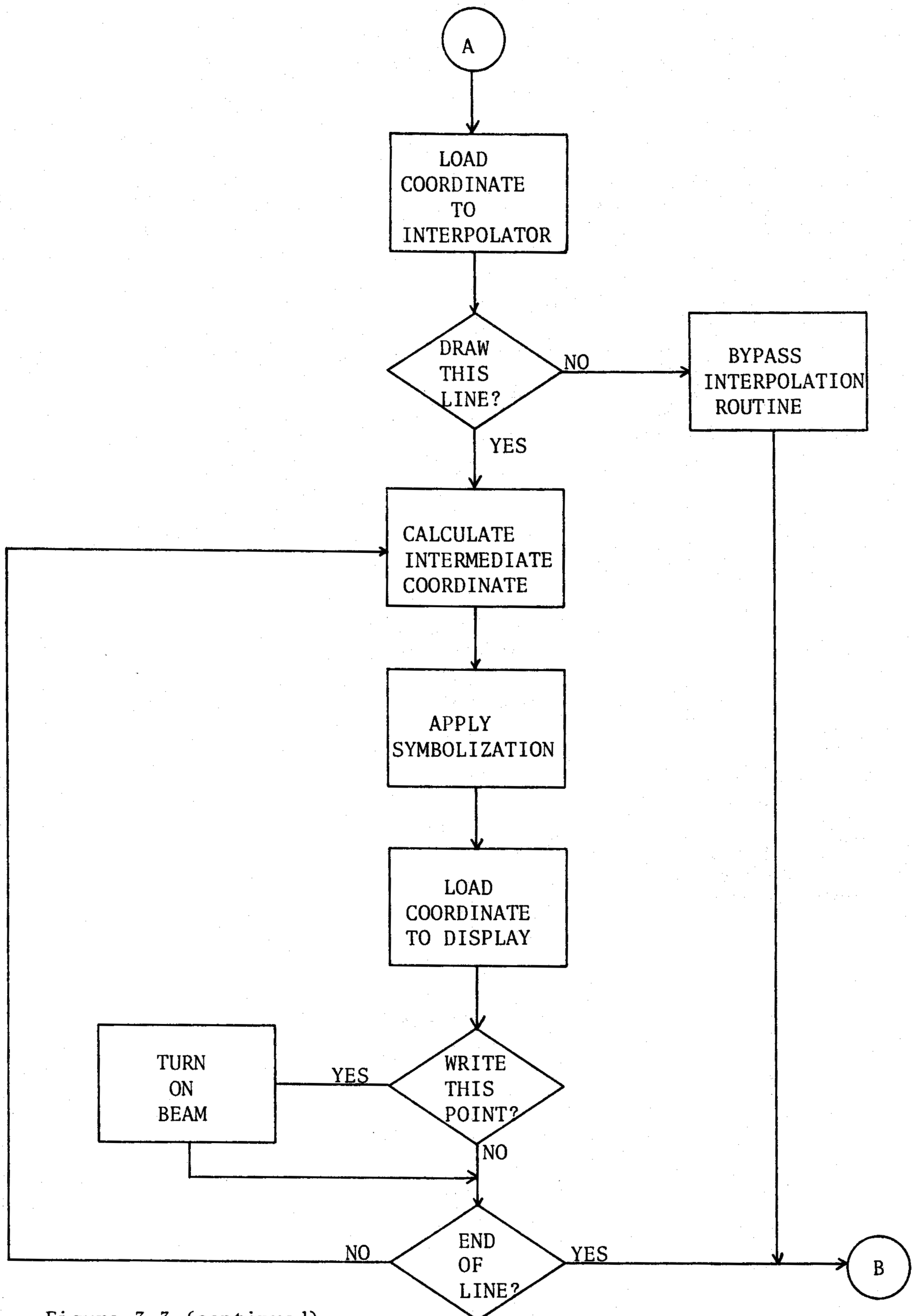

Figure 3.3 (continued)

Differential accuracy (sometimes described as monotonicity) defines the range within which the analogue output of a DAC deviates from equal step changes, for one bit changes of the digital input signal. In most cases, available devices are guaranteed to be within ± 0.5 least significant bits (LSB's). Thus, for a one LSB input step, the output of a typical DAC could change by as much as two LSB's or by as little as zero LSB's. The effect of such a device on the proposed display is as follows. Each axis of the cartographic display requires an input of 15 binary bits (hence a 15 bit DAC) to address every point. Further, one LSB corresponds to a distance on the viewing surface of 0.05 mm., or half the thickness of the narrowest lines to be displayed. Figure 3.4 illustrates the effect which a differential error of ± 0.5 LSB's could have on displayed lines. When such discontinuities repeat themselves several times over the length or breadth of the display, the effect would be not only aesthetically displeasing, but also distracting to the cartographer.

A 15 bit DAC with ± 0.25 bit of differential linearity error can be obtained by employing a sixteen bit DAC and using only the most significant 15 bits (an error of one-half the sixteenth bit is equivalent to an error of one-quarter the fifteenth bit). Figure 3.5 demonstrates the cosmetic effect of ± 0.25 bits of differential linearity

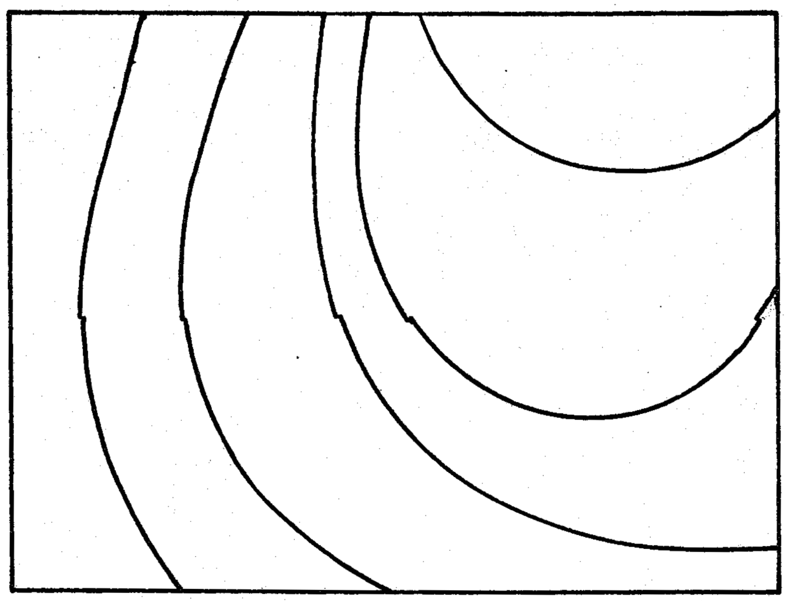

Figure 3.4 Effect of 1 LSb of differential linearity error in D/A converter.

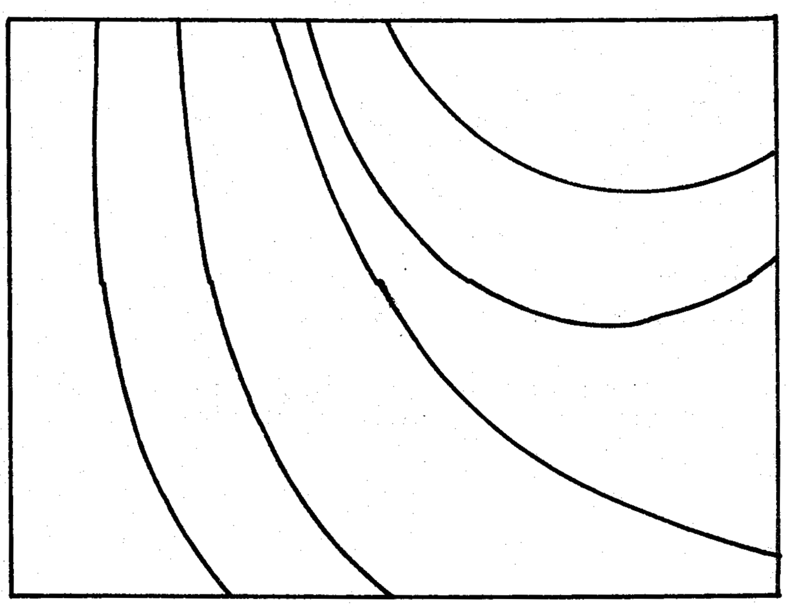

Figure 3.5 Effect of 0.5 LSB of differential linearity error in D/A converter.

error. It was felt that the improvement in image quality obtained by the use of sixteen bit DAC's justified their use in the deflection system.

In addition to cosmetic effects, the DAC's influence the bandwidth of the display. Each time the input to a DAC is varied, the output must be allowed a settling time which is proportional to the size of the input change. For available devices, this settling time is approximately 100 microseconds for a full scale signal change, and less than 20 microseconds for a change of less than 0.1 per cent of full scale. Since cartographic data consist mostly of lines, the change in beam position between consecutively addressed points is usually very small, and the DAC can operate at a rate exceeding fifty kilohertz. It must be pointed out, however, that the overall display bandwidth is significantly lower than this value due to the time required to write each point after it has been addressed (see section 3.3).

Several other technical considerations are important when designing systems with high resolution DAC's. Precautions must be taken against thermocouple effects, voltage drops in short lengths of wire, and external magnetic or electrical noise. Units are available which exhibit an extremely low temperature drift of about seven parts per million per ^{o}C. Nevertheless, some temperature control of these units might be necessary if the ambient temperature varied more than a few degrees during the time the image was being drawn.

3.2.2 Analogue deflection amplifiers

The output from the DAC's is a low voltage or low current signal which is linearly proportional to the digital input. This signal must be amplified to provide the required driving current for the deflection coils. Amplifiers are available which will provide adequate linearity and drive current for this application. The thermal stability of these amplifiers, however, is only about 0.01 percent per degree Celsius. Thus temperature changes, caused by current variations within the amplifiers during writing, can introduce errors in the written image. Fortunately, these errors are not normally visible to the human eye unless they occur between adjacent cartographic features, one written before and the other after the temperature change. This seldom occurs and the image, therefore, is in most cases acceptable. Methods of reducing this problem by means of computer monitored correction of the temperature drift could be built into the system, if found to be necessary.

Air-core coils are used for the high resolution deflection and focusing system since magnetic cores display residual magnetism, resulting in poor repeatability. These coils, and the high current amplifiers required to drive them, are normally obtained as matched units so that the resistance, inductance, current, and stability requirements are achieved.

3.3 Electron Gun and Power Supplies

In order to write a small image, and thus to minimize the size of CRT target required, a high resolution electron gun must be used. The smallest electron beam diameter normally attainable with a conventional CRT electron gun is 0.012 mm. This is achieved by means of a magnetic focusing system and a series of physical baffles in the gun. In addition to limiting its electron beam diameter, the baffles have the advantage of producing an electron beam with a cross sectional density which is almost constant rather than Gaussian. This results in a written point on the target which, because of its sharply defined edges, appears to have higher contrast.

The minimum time required to write a point of acceptable density is a function of the beam current which the electron gun can deliver. The baffles in a high resolution gun severely restrict the available current, yielding an effective writing time of approximately forty microseconds per point on a sodalite.Br target. This figure is based on the assumption that most data are lines, where adjacent points will have an overlap area of 35 percent. It is also assumed that the beam current is not in most instances switched off during the time between the writing of one point and the addressing of the next, since in line data these points do overlap. Thus the beam current which can be delivered by most high resolution guns, limits the effective 'point-mode' addressing rate to approximately 25 kilohertz.

The electron gun requires several supply voltages. The cathode is operated near ground potential, with a control grid in front of it biassed at approximately -20 to -50 volts. The electron beam is usually switched off and on with a voltage applied to the grid. This Z axis modulation is supplied by an amplifier which has inputs both for normal writing signals, and for inhibiting the beam to prevent damage to the CRT in the case of any electrical failure. Between the control grid and the target are one or more accelerating anodes which operate at potentials of the order of 1000 to 2500 volts. Finally, the CRT target is maintained at a voltage of +30 kilovolts to provide the final beam acceleration. This high voltage supply must be very well regulated since deflection sensitivity, and hence beam position, are functions of the beam acceleration voltage.

3.4 The CRT Envelope and Target

The glass CRT envelope is similar to that used in most standard cathode ray tubes. Although the actual fabrication of such an envelope presents no difficult technical problems, it does require special equipment. The most critical component of the envelope, in this case, is the faceplate. It must be made of very flat, high quality optical glass so that it does not interfere with the projection of the image. The entire envelope, including the magnetic deflection coils, must be shielded to prevent interference from external electrical and magnetic noise.

The target is supported within, but not in direct contact with, the glass envelope in order to avoid excessive heating of the glass each time an image is thermally erased. The target and faceplate must be parallel to each other and both must be perpendicular to the electron gun within very close tolerances. The target is aligned when mounted, while the alignment of the faceplace is done when it is welded to the envelope. This technique of alignment is presently used in the fabrication of high resolution CRT's.

The suspended target is of optical grade glass on which is deposited a layer of tin oxide, indium-tin oxide or a similar transparent conducting material. The conductor serves two purposes. Firstly it forms the final acceleration anode for the electron beam and collects the electrons which strike the target. If these electrons were not conducted away, then a negative charge would build up at the point being written and the effective beam acceleration would be reduced. The beam would also be spread by this charge, causing unwanted enlargement of points or lines.

Secondly, the transparent conductor forms a resistive heater which is used to erase the image on the target. The time required to erase an image is two to five seconds, although several more seconds must be allowed for the screen to cool again before a new image can be written and retained.

A thin layer of powdered sodalite.Br is settled onto the tin oxide. The settled powder technique is well known in the fabrication of phosphor CRT targets. A powder is used because there is no other known form of sodalite.Br which can be made sensitive to electron beams (see section 2.3.5).

The size of the CRT envelope is dictated by the dimensions of the target. The minimum target size on which a complete high resolution image can be drawn, in turn, is limited by the resolution of the electron gun. The minimum diameter of the electron beam is 0.012 mm. In order to achieve the thinnest specified line width of 0.1 mm. on the projected image, the line drawn by this electron beam must be optically magnified by a factor of eight. Thus the CRT target cannot be less than one-eighth the size of the 130 cm. by 100 cm. viewing surface, or 16.3 cm. by 12.5 cm. A CRT faceplate diameter of approximately 23 cm. is necessary to enclose this target.

3.5 Optics

The optics system includes a condenser lens and a large aperture projection lens system with a fixed magnification of eight times. An infrared filter is inserted between the projection lamp and the condenser lens to prevent excessive heating of the target. Folding of the optics path is employed to reduce problems of installation in confined areas.

The linearity of the projection lens is not critical; errors of two or three percent would be acceptable. Since high resolution lens systems typically achieve linearity values of better than 0.5 percent, linearity presents no constraint in the selection of an optics system. The specification of resolution, on the other hand, is stringent. It is necessary to be able to create, on the projected image, a sharply defined line with a width of only 0.1 mm. In order that this line does not appear to be severely blurred, the resolving power of the lens must be appreciably higher than the width of the line. It is estimated that a lens which can resolve at least a quarter of the line width, or about forty points per mm. in the image, is required.

3.6 Proposed Later Improvements

Several modifications were considered for the large screen display. It was intended to incorporate these after the feasibility of the prototype system had been proven. The most significant modification was to be a magnetically positioned movable target assembly. This would contain four targets on a disc which could be rotated inside the CRT. With such an arrangement, one target could be erased while the second was being viewed, the third being written, and the fourth cooling after erasure (see figure 3.6). This would permit a new image to be drawn without waiting for the previous image to be erased, and the target then to cool. With some software modifications, a new image could, in fact, be generated while data editing was being carried out on the previous image. Alternatively, the user could create different images on the four sections of the target, then alternately select any of the four for viewing as he proceeded with his work.

A rotating target assembly would allow the target to be moved out of the axis of the electron gun. It would then be possible to place the projection optics behind the target, as shown in figure 3.6. This configuration has several technical advantages. Each target could be fabricated as a section of a sphere, with its radius such that the focal length of the electron beam could remain constant. This would eliminate the need for dynamic focusing of the beam. In addition, the beam always would be perpendicular to the point where it impinged upon the target. Thus elliptical distortions of the beam cross-section, and the resultant resolution losses at the edge of the target, would be eliminated. Other advantages include the feasibility of

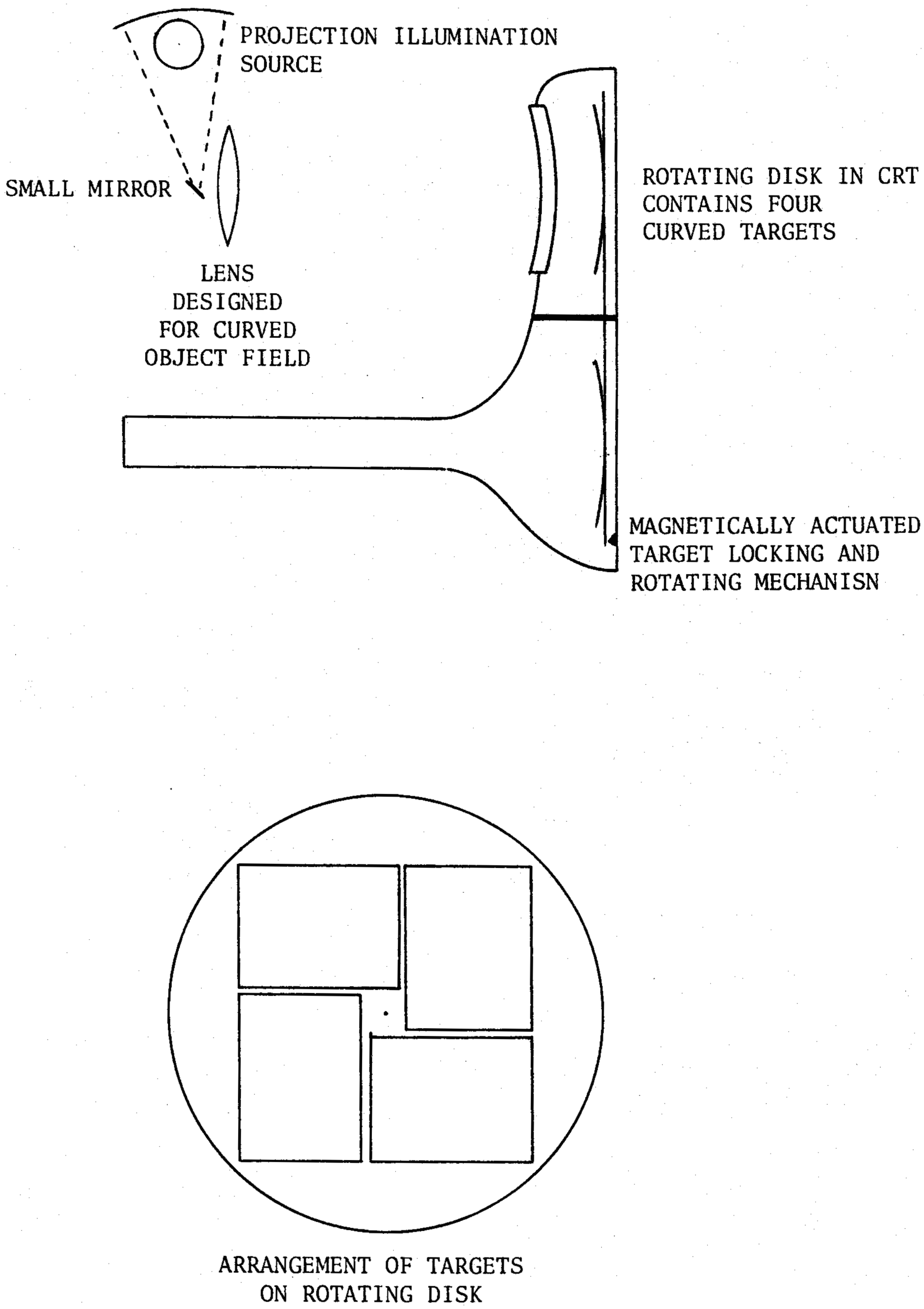

Figure 3.6 CRT with rear projection and multiple curved targets.

employing deflection angles of as much as 40 degrees, without introducing unacceptable distortions.

The curved target could also result in a simplified optics system. One major difficulty in designing optics is to generate a flat image field when the object being projected is also flat. The image field resulting from a flat object tends to be curved unless compensation to correct this fault is incorporated into the lens design. The use of a curved CRT target would reduce this design constraint, and might make the design of a special large aperture lens system with high resolution less difficult.

A rotating target assembly removes the need for a transparent target because the projection optics and the electron gun can be on the same side of the target. Several advantages result from this arrangement.

1. The cost of fabricating a transparent conducting layer on the target is averted.
2. A metal target could be designed which would cool more rapidly after thermal erasure.
3. A reflecting target would return more light to the projection lens.
4. A reflecting target would cause the projection light to pass through the cathodochromic material twice. This would result in more light absorption in written areas, producing a higher contrast image.

5. A concave target would reduce the solid angle over which diffused light is scattered, yielding a brighter image.
6. A concave target would result in better light distribution over the target surface, and therefore less vignetting in the projected image.

By means of a low power laser, or a phosphor combined with the dark trace target material, it might be possible to create a write-through pointer for the display. The pointer would have a resolution lower than the displayed image, and would usually serve to identify an area rather than a specific coordinate.

Finally, it was intended to investigate the feasibility of selective erasure, which has been accomplished in experimental systems by means of the same electron beam which performs the target writing function. This could further simplify the entire system by removing the need to use thermal erasure. However, in systems presently under study, it would be necessary to draw a negative image, i.e. a black image background with white lines.[223]

CHAPTER FOUR

THE EXPERIMENTAL SYSTEM

Experimental cathode ray tube and optical systems were employed to investigate the feasibility of the prototype display described in Chapter Three. Removable cathodochromic targets were mounted in an electron gun assembly, inside a demountable vacuum system. After dark trace images had been written, the targets were removed from the vacuum and used for a) a study of their contrast and image retention properties under various conditions of optical exposure and temperature; and b) investigation of the suitability of various optical systems for the projections of dark trace images. The experimental work is summarized below. Appendix Three outlines the methods attempted and the procedures employed to obtain these results.

4.1 Electron Beam Apparatus

The bell jar, containing an electron gun and target assembly, was evacuated by an oil diffusion pump capable of achieving a vacuum below 10^{-7} Torr. Although the vacuum system was outfitted to provide all the required electrical and mechanical connections to the electron gun, no suitable optical access to the target was available. It was thus necessary to remove targets from the vacuum in order to project the dark trace images; this was inconvenient, but presented no serious technical limitations to the experimental work as no drastic change in the target or image occurred.

A modified gun with electrostatic deflection was used; the coils of most magnetic deflection displays can be physically damaged if placed in a vacuum. An acceptable electron gun for this work was obtained from a commercial CRT. Since the oxide cathode in such a device is irreversibly damaged by exposure to the atmosphere, it was replaced with a tungsten filament cathode of the type used in electron microscopes. The supplies used to drive the gun were fitted with controls and meters enabling beam current, filament current, and acceleration voltage to be varied and monitored. Beam deflection was provided by specially designed amplifiers driven from ramp generators.

4.2 Fabrication and Colouring of Powdered Targets

KCl was used as the cathodochromic material on the targets due to its availability and because it did not require special processing techniques to be made cathodochromic. Powdered KCl was sprinkled into a tank containing 91% isopropyl alcohol and 9% water, through which it settled onto a copper surfaced target suspended in the bottom of the tank. The copper would serve later both as a high voltage acceleration anode and as an electron collector during the writing of an image. The water contained in the alcohol dissolved the surfaces of the KCl particles slightly, with the result that when the targets were dried, the particles adhered to the copper and to each other. Satisfactory target stability was thus achieved without adding binders which might have influenced the cathodochromic properties of the KCl.

The targets were mounted in the bell jar and exposed to electron beam irradiation at a vacuum of approximately 10^{-6} Torr. Line patterns were written over a wide range of acceleration voltages (2 to 30 KV), beam currents (0.1 to 100 uamps), and writing times (0.1 us to 30 minutes). The targets were then removed from the vacuum chamber and the image densities observed both at room temperatures and at the higher temperatures which occurred during optical projection.

The observed bleaching effects at room temperature were comparable with those described in the literature, although image retention times were longer than expected. The two bleaching stages, resulting from first optical mode, then thermal mode, colouring were observed. Very light traces would disappear completely in under an hour, while somewhat darker ones would partially bleach, becoming faint, but more permanent, traces. No visible bleaching of very intense traces could be observed over a period of several days, apparently because the optical mode colouration represented only a small part of the total darkening in these traces. Written images placed in darkness at room temperature retained all but the faintest traces for several days, while some of the darkest traces were still visible three months later.

Higher temperature studies revealed an unexpected result. The more intense images, when placed under a projection lamp, did not fade as quickly as expected. Some traces bleached only slightly, despite two hours of exposure to intense light and temperatures near $100^{\circ}C$. Although the explanation of this apparent contradiction with published data was not known, the result indicated that reported bleaching problems of KCl, when used as a dark trace material for projection display systems, might possibly be overcome. Because of the previously mentioned advantages of cost, availability, and ease of processing which KCl exhibits, it appeared that there might in fact be some justification for selecting it in preference to sodalite.Br as a target material in a commercial device. Thus it was decided that further tests should be conducted to determine the cause of the long image retention time and its applicability to a production display device.

4.3 Investigations of Evaporated Targets

Most KCl targets described in published literature were produced by evaporation methods. It was thought that the different method of target fabrication might be the source of the unusually long bleaching times observed for the settled powder KCl targets. A variety of evaporated KCl targets was therefore fabricated in the vacuum facilities, and the image retention properties of these targets were investigated.

Microscope slides were used as substrates for the evaporated KCl targets. Onto these, a thin layer of aluminum was deposited to serve as an anode during later electron beam colouring. KCl was evaporated onto the aluminum surface, and its thickness was monitored. As the KCl was heated, the water of crystallization was released before the KCl reached a temperature high enough to evaporate. This was indicated both by the fracturing of small KCl particles and by the sudden increase in vapour pressure which occurred within the vacuum chamber when a sample of KCl was heated for the first time. Neither effect was observed during subsequent reheating of the same sample.

KCl was deposited to a thickness of eleven microns, this being the maximum depth to which 30 KV electrons could penetrate.[225] The resulting surface appeared to be 'milky'. Under a microscope it was observed as a mass of small crystals forming a very roughly textured surface.

These polycrystalline targets were irradiated with the electron beam and the anticipated colouration occurred. However, after the electron gun was switched off, the fainter traces faded within a few seconds, while even the most intense colouration was barely visible after five minutes. Because of the observed loss of water of crystallization in the KCl when evaporated targets were produced, it was hypothesized that the water, which had not been driven out of the settled powder screens, might be the reason for their unexpected image retention. Further tests with opaque and transparent targets appeared to confirm this.

Settled powder screens containing water could not be used in a production CRT since the water would be lost gradually as the KCl was heated, both by the thermal erase cycle, and by the electron beam during writing. It might, however, be possible to find a material which would have the same effect as water on the image storage properties of KCl, but which would also be stable in an evacuated environment. This research was not carried out.

4.4 Optics

The two primary requirements for the optical projection system were: a) that it produce a high resolution image of good viewing quality, and b) that it collect adequate light to produce an acceptably bright image. Studies were carried out on several lens systems to determine if these properties could be obtained. In each case an image from a test pattern of approximately the required CRT target size and resolution was projected, and the quality of this image at eight times magnification was observed. Finally, the light-collecting capabilities of lens systems which could provide adequate image quality were estimated.

4.4.1 Image quality

Measurements of image quality and resolution were first carried out on lenses designed for projection systems. These included slide projector lenses with physical apertures of 2.5 to 4.0 centimeters, and opaque projection lenses with twelve centimeter apertures. It was found that the lenses used in slide projectors could only reproduce a small area of the test pattern. This image was of poor quality, with severe blurring at the edges of lines. Chromatic aberrations and severe curvature of the image field were also observed. Opaque projection lenses were able to project the entire area of the test pattern, however, aberrations were so severe that lines thinner than about 0.2 mm. on the test pattern appeared only as grey shadows in the image.

The suitability of lenses designed for cameras and photoenlargers was investigated. Many of these lenses were able to produce a very clear image of a portion of the test pattern, but most were not designed for projecting a large area. Attempts to reproduce a larger area resulted in severe curvature of the edges of the image field. However, a lens designed for large format studio cameras was located which could reproduce a clear, although not acceptably bright, image of the entire target.

Lenses which could produce an acceptable image from all or part of the test pattern were tested using the KCl targets. The granularity of the settled powder screens, which had a coarse surface texture due to the primitive settling methods used, were very noticeable in the projected image. The dark traces were, never the less, clearly visible and exhibited good contrast. The resolution of the magnified image was high enough to permit the rough edges of the traces, resulting from screen granularity, to be seen clearly.

Projection of images written on evaporated targets were, however, much more difficult to study, as they faded very rapidly when placed under the projection lamp. Nevertheless, for the first few seconds after they were placed in the projection system, they produced sharp, high contrast images. Then the traces began to fade, producing a lower contrast, but still a sharply defined image.

4.4.2 Image brightness

Camera lenses were capable of producing an image of the required quality and resolution for cartographic applications. The lenses tested, however, had long focal lengths and small physical apertures. The amount of light which they collected was inadequate for display purposes, as the image could only be seen in a dark room. An operable display required a lens which could collect much more light, but maintain the same high image quality.

The KCl target is essentially a Lambertian reflector, that is, it scatters incident light almost equally over a solid angle of 180 degrees. An appreciable amount of this reflected light could be collected only by a projection lens which was at least as large in diameter as, and positioned very close to, the target. Unfortunately, the aberrations in large aperture lens systems are very difficult to correct, and the existence of a high resolution lens approaching the CRT target size (12.5 cm. by 16.3 cm.) has not been reported.

For most cases in which the projection lens is smaller than the target image to be projected, the amount of light collected is directly proportional to the numerical aperture (NA) of the lens. Numerical aperture is defined as the ratio of the effective diameter of the lens to its focal length. As an example, a 10 cm. diameter lens with a focal length of 40 cm. will collect approximately the same amount of light as a 20 cm. diameter lens with a focal length of 80 cm. However, this rule must not be carried to extremes in practical systems, since a small aperture placed very close to the target will collect almost all the light from the centre of the target, but very little from the edges, resulting in severe vignetting.

The method of designing high quality lens systems has tended, during recent years, to turn away from 'ray tracing' which is a technique of determining the path of light beams as a function of the refractive indices of the lenses. This is being replaced with more sophisticated calculations based on the phase and velocity relationships of the light waves being propagated. Although superior lenses can be designed by the latter method, this work often requires iterative solutions which need to be solved by powerful computers. Since the necessary technical support was not available for such calculations, it was necessary to depend upon lens designers and suppliers for information on the types of lens systems which could be fabricated or were available.

The most useful lens located had an effective aperture of 9.6 cm. and a focal length of 24.4 cm. This lens was not available for testing, but specifications supplied by the manufacturer indicated that it could produce an image of satisfactory viewing quality and resolution. Therefore calculations were made to determine if the lens could collect enough light to produce an adequately bright image.

The brightness of a projected image can be estimated from the following equation:[255]

$$B = \frac{W\ K_b\ K_o\ G}{100A}$$

where:

W = the power used by the projection lamp in Watts,

K_b = the useful light output of the projection lamp, in lumens per watt,

K_0 = the efficiency of the optical system, in per cent,

G = the gain of the viewing screen,

A = the area of the viewing screen, in square feet,

and B = the brightness of the projected image, in foot lamberts.

These constants are discussed in the following paragraphs as they apply to the proposed system.

Projection lamps have a practical power limit of about 1000 watts for incandescent bulbs, and 2000 watts for short-arc Xenon lamps. A 2000 watt lamp requires special power supplies, forced air or liquid cooling, and filters, either water or dichroic mirrors, to block excess infrared light from heating the target and erasing the image. The bulbs are expensive and have lifetimes of only about 1000 hours. Finally, the projection lamp in such a system would dissipate more heat than the entire computer system with which it was intended to be used, thereby possibly necessitating the addition of, or modifications to, air conditioning systems. Despite these difficulties, however, a 2000 watt projection lamp would be technically feasible.

The conversion efficiency of Xenon to useful light in the visible spectrum is about 25 lumens per watt. Although total radiant energy output is many times more, only the portion of the spectrum to which the eye is sensitive may be considered to be useful. The optical efficiency of a transparency projection system employing a high quality condenser lens and a mirror behind the projection lamp is normally in the order of 3 to 7 per cent, and is generally estimated as 5 per cent.[255] In this estimate, it is assumed that all of the light which passes through the target is collected by the projection lens. Opaque projection systems exhibit all of the same losses as their transparent counterparts. In addition to these losses, the loss of light resulting from the projection lens being unable to collect most of the light which leaves the target must be added. For the lens and target size considered here, approximately two per cent of the light reflected from the target will strike the projection lens. Thus the overall optical efficiency of the system would be 5 x .02 = 0.1%. The losses which would be encountered in illuminating the target with a light source positioned outside the optical axis, necessitated in order not to obstruct the projected image, have not been considered. These would be appreciable unless a complex and expensive condenser lens system was used.

Viewing screens can be Lambertian reflectors, or as is often the case in practical systems, they can be designed to reflect most of the light over a restricted viewing angle. For the latter situation, the screen is said to have gain,[16,258] since a larger amount of light can be directed towards the viewer's eyes. This is accomplished by covering the surface of the viewing screen with small spherical glass beads or a similarly shaped surface which reflects most of the light in a direction parallel to the axis of illumination. It is doubtful whether a screen with gain would be acceptable to a cartographer, as areas viewed at large angles would exhibit low brightness. The gain of the screen for the cartographic display is assumed to be unity.

Using the figures listed above, the brightness of the 1.3 square meter (12 square foot) screen area is found to be about four foot lamberts. This optimistic value is five times lower than has been suggested as the minimum for a projection display [255] and would necessitate the use of an almost completely dark room in order to have an acceptable image brightness. Since the cartographer must have the room illuminated to a level that enables the easy reading of printed maps, that is, a value of approximately 20 foot lamberts, it would not be possible to use this display under lighting conditions needed for reading maps.

Variations are suggested in the next chapter which might, however, provide methods of increasing the brightness of the display system to an acceptable level.

4.5 Transparent Projection

It was determined that a satisfactory opaque projection display could not be achieved using the methods described. Before investigating major modifications to this system, the possibility of using a transparent KCl target and matching projection system was studied. Projection experiments using a transparent test pattern and previously tested lenses confirmed that both light output and the image quality required could easily be accomplished. Tests were therefore carried out on transparent KCl targets to determine if a trace approaching adequate contrast could be written.

Melamed[236] has described the optical properties of diffuse reflecting surfaces whose particles are large in comparison with the wavelength of light. He has shown that the amount of light absorbed by a powdered surface of a specified index of refraction and absorption constant is often much higher than the light absorbed by a transparent material of the same properties and coloured to the same depth. On the basis of this information, it was anticipated that the absorption coefficients in transparent KCl targets should be lower than had been observed for the opaque targets. Tests were required to determine if this lower contrast actually would be observed for various methods of target preparation, and if it did occur, whether it was so severe as to prevent a successful projection display of this type from being built.

Tin oxide or tin-indium oxide is usually the material used on CRT targets requiring a transparent conductive anode.[230-233] However, the apparatus and techniques required to successfully fabricate such a conductive layer were not available. This problem was overcome by vacuum depositing an aluminum reflective layer beneath the KCl, then projecting an image using reflected light. This provided the added advantage of causing the projected light to pass twice through the KCl, resulting in twice the optical absorption in darkened areas.

Four different types of transparent targets were fabricated:

1. Anhydrous polycrystalline; by evaporating a layer of KCl onto an aluminum surface, then polishing the KCl so that a smooth, transparent surface resulted,
2. Hydrated polycrystalline; by pressing KCl discs using a method originally developed for spectroscopy,[226]
3. Single crystals; by growing crystals from a melt, then cleaving thin layers from these and fastening

them to an aluminum target,

and 4. Amorphous, by a) melting, then quickly freezing, a thin layer of KCl on Vycor Glass, and b) by vacuum depositing a thin layer of KCl onto an aluminum target.

The above targets were irradiated for periods ranging from a few seconds to two hours. Darkening of the KCl occurred but, in all cases, these traces were of very low contrast and appeared transparent, similar in density to that of a pale blue glass. Projection of these targets produced images in which the traces were just visible. The traces faded very rapidly, with the exception of those in the pressed discs, which remained for several days. Thus it was not possible to create a projection display using KCl in a transparent form as the target material, employing the fabrication methods described.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

A preliminary survey of the state-of-the-art in display technologies indicated that, although a large amount of development work would be required, a large screen, high resolution display suitable for cartography should be technically feasible. This should be achievable by the use of a CRT with a cathodochromic, optically diffusing target of sodalite.Br. The image written on this target would be optically enlarged and projected onto a 'rear projection' viewing screen.

It has however been determined that, due to inadequate brightness of the projected image, such a system cannot be achieved using existing equipment and the hardware configurations described in this thesis. An operable system might be achieved if unique system components and sub-assemblies were designed and fabricated. Such an endeavour, however would be excessively expensive. Because of the limited number of such displays required for cartographic applications, other markets for the display would have to be found before such development costs could be justified.

The experimental and theoretical studies described in this thesis have considered only dark trace targets of conventional design, and optical systems which are presently available. A unique design which optimizes and matches the properties of the target and the optical system might produce the brighter projected image required to make this display usable. There are several areas in which modifications could improve system performance.

An optics system is required which would be optimized for this application. Several features could be incorporated:

1. All lenses tested had been designed for variable focal length applications. It might be simpler to design a fixed focal length lens with a magnification factor of eight.
2. A lens with a narrow spectral bandwidth matched to the target's absorption band should be used in conjunction with a bandpass optical filter. This would minimize the problems of chromatic aberration.
3. A lens designed to project an image from a concave target surface would reduce the correction needed for curvature of the image field. Perhaps an aspherically shaped target would be even more advantageous. A curved viewing surface (projection screen) could also be used, although this would probably be expensive to fabricate.

A projection lamp might be designed which would more nearly match the absorption band of the photochromic target.

By increasing its effective optical efficiency, that is, the lumens per watt which contribute to usable image brightness, both operating costs and the cost of equipment for cooling the projection lamp could be reduced. Variations in the position and width of light emission bands in gas arc lamps can be controlled by varying the pressure and mixture of the gases used.

A relaxation of demands on the optics might be achieved by reducing the electron beam diameter. This would allow the target size, and hence the required projection lens aperture, to be smaller. A unique electron gun, focusing, and deflection system would be required. However, the minimum size of particles which could be used for the cathodochromic target would need to be determined. Both experimental and theoretical evidence suggests that particles smaller than 15 microns in diameter would begin to yield a lower contrast image.

Finally it might be feasible to change the reflecting properties of the target so that it would, at least to a limited extent, collimate the light being reflected, without severely reducing the image contrast. Sodalite.Br must be used as a sensitized powder in order to be cathodochromic. Perhaps by controlling the shape of these powdered particles, in particular by using spheres, a measure of control over the direction of the reflected light could be obtained.

An order of magnitude increase in image brightness over that available with existing components is desirable. However, even a four fold increase in image brightness, combined with a reduced power consumption for the projection system, could result in a practical display device.

APPENDIX ONE

SELECTION OF DISPLAY SPECIFICATIONS

The parameters which were selected as guidelines for this feasibility study are listed in the Introduction. This appendix outlines the criteria considered in deriving these parameters. Because of the absence of 'hands-on' experience with a large area display, it was necessary to make some assumptions based solely on experience with manual systems.

A1.1 Display Size

The display was intended primarily for cartographic applications. Its dimensions were chosen to accomodate the majority of smaller map sheets currently produced. These include the hydrographic charts supplied by the Canadian Government, and the 7.5 minute 'quad' sheets made by the United States Department of the Interior.

It was felt that a smaller display would limit the user, by requiring the frequent drawing of map segments, and by failing to serve its primary purpose of providing an overall view of the finished map product.

A larger display was not specified for three reasons.

1. It was realized that this display would be approaching the state-of-the-art in both the areas of optics and of electronic deflection systems. In order to minimize these problems, it was necessary to have the display as small

as the cartographic requirements could allow.

2. A larger display would be more expensive, and hence might not be marketable.

3. The advantages to the operator of further increases in the size would diminish rapidly. He would need to move away from his keyboard, and also perhaps his map sheets, in order to view the extremities of the display. In addition, the human eye and mind can view and correlate only a limited quantity of information at one time. It was felt that this limit was being approached and that presenting more information would not greatly benifit the operator.

A1.2 Screen Resolution

This parameter was determined on the basis of existing cartographic requirements. The narrowest line which is normally drawn by a cartographer is 0.1 mm. In order to approach this on a display, a resolution of ten spot diameters per mm. is required.

A1.3 Addresseable Resolution

Ideally, the addresseable resolution should be so high as to prevent single points in a line or area from being visible. This would be technically difficult, if not impossible to achieve for the large area display. A compromise was therefore necessary.

The eye can resolve points which subtend angles as small as

0.23 minutes of arc under ideal conditions of lighting and contrast.[16,17] At a normal viewing distance of 15 cm., this angle corresponds to a distance on the viewing surface of 0.01 mm. Fortunately, these ideal viewing conditions are seldom found in practical systems. It has been suggested that an angle of about one minute of arc is normally considered adequate resolution for displays which are to be viewed by the naked eye.[18] This figure was accepted for the proposed display.

A1.4 Point Addressing Capability

It is necessary that cartographic data be handled in a vector or line form inside the computer, so that their manipulation and storage be fast and efficient. It would require unacceptably large amounts of time and computer power to convert the data for a map sheet into a scan format. Thus it was necessary that the display be compatible with the existing data structure. This was most easily implemented by the use of a point addressed display.

A1.5 Display Cost

It was necessary that the display remain proportional in price to the rest of the cartographic edit system. Although useful, the large screen display was certainly not indespensible, and could not be justified if it doubled total system cost. As the hardware price of the edit system is approximately forty thousand dollars, it was considered that twenty thousand dollars was the maximum price at which this display could be marketed.

A1.6 Erase and Redraw Time

An erase and redraw time of two minutes was considered the minimum that was technically feasible. It was estimated that the display would be erased and redrawn once every thirty to sixty minutes on average. Two minutes represented a small percentage of this time, and was considered acceptable because it did not present an appreciable limiting effect on production rates. in addition, it was felt that the display could be redrawn while the operator was editing on a smaller interactive display. Thus, in most circumstances, no operator time would be lost while the display was being updated.

A1.7 Image Storage Time

It was estimated (A1.6) that the operator would be working with the same image for periods of up to an hour. During this time he should not be delayed while the image is redrawn, nor should he be required to view a fading or low contrast image. Thus a minimum image storage time of one hour was specified.

APPENDIX TWO

THE PRESENT STATUS OF DISPLAY TECHNOLOGY

Much money and effort are being invested into the development and improvement of display technologies and display systems.[21,48] In the next decade this can be expected to revolutionize the types of displays available, but, at present, the only competition with the long established reign of cathode ray tubes is provided by gas discharge displays, and laser systems which are mainly being used for hard copy output.[24-26] The description of display technologies which follows includes these and others available, together with many systems which are currently being developed. Some of the experimental systems described may not meet all of the requirements, but others may well make the cathode ray tube as obsolete as the transistor has made the vacuum tube.

Display systems have been categorized according to the four methods of addressing: cathode rays or electron beams (A2.1), lasers (A2.2), direct or electrical addressing (A2.3), and magnetic addressing (A2.4). Described under each heading are the displays employing targets or viewing surfaces compatible with that mode of addressing. A summary is given in table A2.1. Tables A2.2 through A2.5 show, for each of the four addressing methods, the ability of the systems to function as large screen displays.

A2.1 Cathode Ray Tube Displays

Cathode ray tube technology is the most mature and widely used for displays today.[28] Because of mass production techniques, their cost is low

	Cathode Rays	Laser	Direct Address
Cathodochromics	X		X
Photochromics		X	
Light Emitting Diodes			X
Plasma Displays		X	X
Liquid Crystals	X	X	X
Diffracting Surfaces (Liquid)	X		
Diffracting Surfaces (Solid)	X	X	
Amorphous Semiconductors		X	
Photographic Type Films	X	X	
Electroluminescent Phosphors			X
Single Crystal Ferroelectrics	X		
PLZT Ceramics		X	
Passive Reflecting Surface		X	
Dipolar Suspension			X
Electrophoretic Suspension			X
Phosphors	X		
Magnetic Bubbles (Solid and Liquid)	Magnetic Addressing X		

Table A2.1 Addressing Methods for Display Materials unless special systems are required. Many years of development have produced electron guns which can produce a spot of 0.012 mm. in diameter (or less in special systems[29]) while equally sophisticated deflection systems can address up to 10^4 or more points. The major limitation of cathode ray tubes for large screen displays is the physical restriction on the size of evacuated glass envelopes; and hence, on the target area which is practicable to build. Curved faceplates are limited to approximately 75 cm. in diameter[30] while flat faceplates should not exceed 25 cm. Because of limitations in target size, the only practical way in which a cathode ray tube can be used to produce a large image is by optical projection means. The optical system which is employed depends upon the type of CRT target and the image parameters required.

A2.1.1 Phosphors

Phosphors are the best known target materials for cathode ray tubes. They are available in a large variety of colours, with persistances from microseconds to seconds.[31,32] Multicolour displays are possible using phosphor matrix targets in which a number of electron beams address different phosphor dots, as is familiar in the shadow mask CRT used in colour television. In beam penetration tubes the acceleration voltage[33,34] or current [35,36] of the beam is varied to excite different phosphor layers on the target surface. At present only voltage controlled systems have moved beyond the laboratory; but a combination of current and voltage control could eventually produce a display with a full colour spectrum and grey scale, both of which are lacking in present beam penetration tubes.

At very low beam currents and with correspondingly low brightness, the

CAPABILITY	PHOSPHORS	LIQUID CRYSTALS	DIFFRACTING LIQUIDS
Large size- 130x100 cm. viewing area	with projection	with projection	with Schlieren projection
High Resolution 1000 lines	yes	yes	yes
Very high Resolution 10,000 lines	no	no	no
Contrast at Maximum Resolution	Good in subdued light	high	fair
Storage Mode	with limited brightness and resol.	yes	no
Non-store Mode	yes	yes	yes
Write-through Mode	yes	no	no
Erasure	page	page	---
Brightness	poor for high resolution	high	high
Grey Scale	in refresh mode only	no	yes
Storage Time	hours	days	---
Colour	in refresh systems only	no	in some systems
Cost	low to moderate	---	high

Table A2.2 Cathode Ray Tube Display Systems

DIFFRACTING SOLIDS	FILMS	SINGLE-CRYSTAL FERROELECTRICS	CATHODO-CHROMICS
with Schlieren projection	with projection	projection using polarizers	with projection
yes	yes	no	yes
up to 12,000 lines	yes	---	maybe
good	high	good	good
yes	yes	yes	yes
yes	no	no	no
no	---	---	---
page	no	selective or page	page, possibly sel.
high	high	high	maybe high
good	excellent	good	yes
months	years	up to 40 minutes	seconds to days
instead of grey scale with optics	with superimposed images	no	no
low	high	high	moderate

resolution of phosphors can be up to 80 points per mm. At higher intensities the area of the phosphor which emits light is larger than the size of the electron beam because the phosphor particles which are emitting light excite other adjacent phosphor particles to also emit light. For this reason high brightness and high resolution are not possible simultaneously. Some improvement in apparent brightness and contrast can be gained by the use of filters[37] or louvred films on the CRT screen. These help to reduce the effects of reflected ambient light which tends to 'wash-out' the image. If high resolution is not required, acceleration voltages of up to 75 KV (with adequate X-ray shielding) can be employed to achieve a very bright image which is suitable for creating a larger display directly by means of an optical projection system. Schmidt optics are usually used because a fast, large aperture system can be built more economically.[38,39]

It is possible to create a stored image by using a specially designed phosphor target together with a second gun to flood the entire target with electrons. This is a bistable device with no grey scale. Brightness is limited in these displays,since the problem of a bright point spreading or 'blooming' becomes severe as brightness is increased. Under subdued lighting the brightness of these targets is adequate for direct viewing,but projection is not feasible. Resolution is also limited because of technical problems in target fabrication. At present, storage displays are generally limited to approximately 1000 addressable points across the target face. However, a new display of this type with 4000 addressable points has recently become available from Tektronix. This is perhaps the greatest advance in CRT display technology since the original phosphor storage targets were made available. There is also a possibility that selective erasure of these Targets may become available in the near future. At present only the total target, or 'page' erasure is available.

Another very useful feature of these storage targets is a 'write-through' mode which permits a non-stored image, appreciably brighter than the stored image, to be written on the target without affecting the part of the image already stored. This is accomplished by controlling the time for which a point is addressed by the electron beam. If desired, the entire target can be used in a non-store mode with phosphor decay rates faster than necessary for the thirty to sixty frames per second rate required in real time displays. No form of multi-colour storage tube using phosphors has yet been developed nor has any suggestion of that type of a device been found in the literature to date.

Display systems with storage, selective erasure, and colour have been created by using a local memory to refresh a non-stored image,[40] although systems of this type are normally limited to the resolution of a standard television format. The local memory may be ferrite cores, magnetic disks,[41] or MOS shift registers, all of which are expensive. However, the cost of solid state memory is dropping rapidly; and it may be practical in a few years to purchase sufficient memory for a full colour display presenting a large amount of data and 1000 by 1000 points resolution. Systems such as 'silicon disks'[42] will probably provide this memory in the near future.

Analogue memories are also presently being used to refresh displays of this type for television screen resolution. These include a dielectric coated mesh,[43] analogue rotating magnetic disks, silicon storage tubes,[44] and, in experimental systems, charge coupled or charge injection devices.

A2.1.2 Liquid crystals

Although the existence of liquid crystals has been known for the last fifty years, these materials have remained a scientific curiosity until the last decade. Attempts during the past few years to use them as a display medium have led to a range of fixed format alpha-numeric readouts which are on the market. Graphic displays are operating in the laboratories and may be on the market within five years.

Liquid crystals [45-47] are elongated organic molecules which flow like a liquid but whose molecules show local orientation similar to that of a crystal. These materials are classified as smectic, nematic, or cholesteric depending upon the molecular configuration. The liquid crystal phase occurs as a transition between the solid and isotropic liquid phases in certain substances. Some materials will pass through more than one liquid crystal phase at different temperatures, others may change phases in mixtures, while still others will only exhibit a liquid crystal phase on cooling to a supercooled liquid. Liquid crystals can exist over temperature ranges as small as 0.5° C or as large as 50° C or more.

Liquid crystals exhibiting dielectric anisotropy (either positive or negative depending upon the application) are used for displays, since only these molecules can be oriented or disoriented by electric or magnetic fields. Heat is used to write images in some materials, but erasure is still accomplished electrically.

Liquid crystals can transmit, polarize, rotate the plane of polarization, scatter or diffract incident light as molecular alignment is changed. Molecular alignment can be affected by temperature, pressure, electric fields, magnetic fields, and impurities. Thus, a wide range of potential display methods exist. Detailed information can be found in references listed under the specific methods mentioned in this Appendix.

Very little work has been done with liquid crystals addressed by electron beams for display systems, although it is hoped that they will be able to replace phosphors in some applications where high ambient light levels produce problems of 'wash-out'.[48] The liquid crystal must remain outside the vacuum of the CRT envelope to prevent its evaporation, so addressing can be done only by transferring the charge deposited by the electron beam to the liquid crystal surface. One method is by using an electrical fibre faceplate on the CRT.[49] This faceplate consists of small wires or conducting fibres embedded in a ceramic or glass matrix. It is possible to produce faceplates of up to 10^8 conductors with fibres as small as 0.003 mm. and spaced on 0.03 mm. centres. A charge deposited by the electron beam on the inside of the faceplate is conducted to the outside surface and can be used for electrostatic printing or to activate voltage or current controlled electro-optic materials.

Such a system has been used to operate a liquid crystal display which consisted of a 6 to 12 micron layer of liquid crystals on the outside surface of the electrical fibre faceplate.[50] The image thus created could then be projected using suitable optics.

A2.1.3 Diffracting surfaces

Diffracting targets are of several types. The most familiar is the

Eidophor used for projecting television images.[51,52] The CRT target is coated with a continually flowing film of oil which is distorted by the charge from the electron beam. A Schlieren optics system[53] is usually used to project this image. The Eidophor does produce grey scale and adequate brightness; but the contrast range is limited, producing pictures which appear somewhat washed-out. This system is also costly to build and to operate, because the oil vapour tends to contaminate the cathode of the electron gun, and this cathode must be replaced after relatively few hours of operation. It has been suggested that this problem could be overcome by using an electrical fibre faceplate, and thus keeping the oil outside the CRT.[49]

To produce colour, three separate images are combined optically, resulting in an even more expensive system. Another system has been built by General Electric using a film of liquid plastic instead of oil.[54] It is claimed that three separate diffraction patterns, each of which is intensity modulated, can be incorporated into a raster written by one electron beam. This will yield a complete colour picture from one tube. The projection system costs $40,000 and lifetime of the target is reported to be about 3000 hours. Light output is lower than with the Eidophor system.

A second type of diffracting screen system called a 'Lumatron' uses a solid plastic surface which is again deformed by electron charges when the target temperature is high enough to soften the plastic.[55] In this case, the charge remains on the target and a relatively permanent image is produced which is 'frozen' into the target when it is cooled. Erasure is accomplished by further heating the target to a point where the charge leaks away. By maintaining the temperature of the target at a high value, above the softening temperature of the plastic, a non-stored image can be written. Resolution is claimed to be 70 lines per mm. and colour or grey scale is available, depending upon the configuration of the optics used. No confirmed value for target lifetime is available.

Another diffracting target surface uses a thin, optically reflecting metal film supported a few microns above a glass substrate. This charge deforms the metal film and light is reflected past the stop in a Schlieren optics system to produce a bright spot on the image. Resolution in this device is limited to about television quality, because of the complex grid structure supporting the metal film on the target.

A2.1.4 Photographic type films

Photographic type films have been developed which are sensitive to electron beams.[43] These films are not erasible, so that only hard copy output is possible. When continuous updating of the image is necessary, the high cost of the film makes it impractical for a graphic display.[58] Since the film must be transported through the evacuated cathode ray tube, it is necessary to have a vacuum pump as part of the system. Thus, the initial cost is also very high. However, this type of unit warrants mention since it is the only type of operating cathode ray tube system capable of writing an image with the contrast and resolution requirements approaching those needed for a large screen, high resolution system.[59]

A system has been developed which eliminates the problem of transporting the film through the CRT. A fibre optics faceplate[60] is used to conduct light from an ultraviolet phosphor to the outside surface of the CRT. This surface is in contact with light sensitive film. However, the resolution is reduced both by the faceplate and by the phosphor.

There are different types of electron beam sensitive films. Some are thermosensitive and cause small bubbles to be formed by the heat of the electron beam. These bubbles diffuse any light striking them,so that an image optically projected by transmitted light would be dark where bubbles had been formed, while an image projected by reflected light would be the converse of this. The units described in the literature used light sensitive film requiring image development. Kodak has now an experimental film known as 'ESR film, type 1'[61] which colours immediately and could be projected as it is written. The magenta colour created is similar to that produced by electron beam irradiation of potassium chloride, but the change is not reversible and the application of heat colours rather than bleaches this film. The method of colouration of these electron sensitive films has not been investigated further here,because the permanent images created would not meet the requirements of the system being investigated in this thesis.

A2.1.5 Single crystal ferroelectrics

Single crystal ferroelectrics of the potassium dihydrogen-phosphate family (KDP), which includes all the compounds obtained by substituting Rb or Cs for K, D (Deuterium) for H, and AsO_4 for PO_4, exhibit the Pockels effect and many can be used as voltage controlled light valves for projection displays.[62,63] The most convenient material for this application is KD_2PO_4, called DKDP or KD_2P, which when operated just above its Curie temperature of -53^{o} C requires a switching potential of approximately 150 volts.

The target size in any display system using these materials is limited to about 20 to 50 mm. diameter, by the size of single crystals obtainable. The optical properties of the target are modified by the electron beam depositing a charge on the surface of the crystal. A change in the target potential modifies its secondary emission characteristics and thus, either positive or negative charges can be deposited. Selective erasure is thus possible. Charge storage time is of the order of 40 minutes and resolution is approximately 400 to 700 lines across the target.

To obtain an image, the projection light is passed through a polarizer, through the target by transmission or reflection, then through a second polarizer and onto a viewing screen. Charged areas on the target change the polarization of the light; and hence its intensity, to produce written points on the screen. Because of the limitations in the target size, the requirement for cooling of the target, and the cost of the resulting systems, the only application in which it is potentially useful is in low resolution projection systems.

Some consideration has been given to obtaining bistable properties by operating other ferroelectric materials such as $Gd_2(MoO_4)_3$ below their Curie temperature[61] but this has not proved fruitful.

A2.1.6 Cathodochromics

The last cathode ray tube system to be considered employs a cathodochromic target.[64] Cathodochromic materials, for example KCl and sodalite.Br, darken on exposure to electron beams. There is no literature describing attempts to create a large screen, high resolution display using these materials.

However, it is known that cathodochromic substances are not subject to a spreading of the written areas as are phosphors. Thus, the electron beam diameter is the only factor limiting the resolution of the image, providing that the granularity of the target is small compared with the electron beam size. Cathodochromic targets can exhibit high contrast and storage lasting from seconds to months. Erasure can be by light or heat. Erasure by light is fast but the target exhibits fatigue after less than 10^4 cycles. The result is a permanent darkening of the target. Thermal erasure requires at least two seconds but no fatigue problems have been observed in this mode.

All targets to date have been fabricated by evaporating the cathodochromic material onto the CRT faceplate or by the standard method of settling a powder onto the faceplate, or onto a separate target supported inside the CRT if thermal erasure is to be used. Either method produces a granular, optically diffusing, surface. It was felt that by opaque projection of an image written on this surface, a display of sufficient resolution and brightness for cartographic applications could be achieved. Alternatively by projection of a transparent target made of the same substance, if one could be fabricated, a suitable image might result. Both of these ideas appeared feasible and are the subject of this thesis. For this reason the appropriate spaces in table A2.2 have been labelled 'maybe'.

A2.2 Laser Addressed Displays

The 'ubiquitous' laser, as it has so often been described, has made appreciable inroads into the field of display technology during the past few years. Because of the high spatial coherence of a laser beam, divergence can be kept to a very low level. Thus, focusing by a lens system is essentially only diffraction limited, so that a very small spot can be obtained at distances of several metres from the light source. With suitable deflection systems for the light, this would allow a large screen image to be written directly by the laser beam. Alternatively, the laser can write an image onto a material which acts as a light valve and is modified by the laser beam to create a stored image, which in turn can be projected.

The major advantage of laser systems over CRT's is the fact that no evacuated envelope is required. Thus, there is not the limitation in target size which prevents large CRT images from being directly obtained. The deflection of a laser beam is, however, a problem which has yet to be completely solved. Mirrors can be used in different configurations to accomplish this. By the use of rotating beryllium mirrors, scan rates higher than 10,000 lines per second can be achieved.[44] By intensity modulation of the beam, bandwidths of 100 megahertz can be reached, with the restriction that the data to be written is available in this raster format. A holographically generated diffraction grating has replaced the mirrors in one system[65] to produce bandwidths signigicantly beyond 100 megahertz.

A random format can be achieved by using galvanometer or voice coil (linear motor) driven mirrors, but the speed is limited by the mechanical inertia of the mirrors to a maximum of only a few kilohertz;[80] even less than this is obtainable if high resolution is required. For resolution of the order of 10^4 or more lines, thermal instabilities can, in some cases, make repeatibility very poor.

Solid state deflection systems are available from several manufacturers.

These are of different types which operate by the Kerr effect, the Pockels effect[66] or Bragg modulation. The most successful to date is the acousto-optic deflector.[67] In this type of device, and ultrasonic wave is transmitted through a transparent material causing its index of refraction to change and hence, the direction of the beam exiting from it to be shifted in direction. These systems have not to date achieved a resolution of much greater than 10^3 points, and it may not be possible to increase this by the one or two orders of magnitude necessary for a high resolution display. Theoretical limitations in such properties as maximum deflection angle in the refracting substance before reflection instead of transmission occurs, and the reduced bandwidth which must exist to obtain high deflection sensitivity for a given range of input frequency, have been major difficulties.

Deflection of laser beams can also be accomplished by very high magnetic fields (the Faraday effect) and it is possible that this method could be used. To date the fields required cannot be produced in a device which is practical for a display system. Another system which uses one laser beam to deflect another is claimed to exist[68] but information on its operation has not yet been released.

With very large sums of money being invested in research into laser deflection, it is almost certain that systems suitable for large screen displays will be available when these methods of deflection are perfected. These are outlined in Table A2.3.

A2.2.1 Plasma panels

One interesting device which can be laser addressed is the plasma display.

CAPABILITY	PLASMA PANELS	LIQUID CRYSTALS	DIFFRACTING SURFACES
Large size-130x100 cm. viewing area	no	with projection	with projection
High Resolution 1000 lines	no	yes	yes
Very high Resolution 10,000 lines	---	not yet but will be possible	no
Contrast at Maximum Resolution	high	high	good
Storage Mode	yes	yes	yes
Non-store Mode	yes	yes	yes
Write-through Mode	no	no	no
Erasure	selective or page	selective or page	page
Brightness	high	high	high
Grey Scale	no	no	yes
Storage Time	until erased	months	seconds to hours
Colour	being attempted	no	instead of grey scale with optics
Cost	high	moderate to low	moderate

Table A2.3 Laser Addressed Display Systems

AMORPHOUS SEMICOND.	FILMS	PHOTO-CHROMICS	PLZT CERAMICS	PASSIVE REFLECTOR
with Schlieren projection	with projection	with projection	with Schlieren projection	yes
yes	yes	yes	yes	yes
yes	yes	yes	yes	no
good	high	good	good	good
yes	yes	yes	yes	no
no	no	no	yes	yes
with visible laser	no	no	no	---
selective	no	selective or page	page	---
high	high	high	high	high
poor	excellent	good	fair	good
months	permanent	seconds to minutes	minutes	---
no	with separate overlays	no	no	good
moderate	high	moderate	moderate	very high

It is possible to trigger individual cells of a plasma panel by light. This would allow writing of images with high brightness and contrast but with limited grey scale and without selective erasure. The resolution of plasma panels is also limited to about 60 lines per inch so it is improbable that this type of system will find widespread use.

A2.2.2 Liquid crystals

Of far more immediate interest is the use of liquid crystals as a storage medium. Here an infrared laser (1.06 microns) can be used to heat a thin layer of liquid crystals.[69-72] The result is a phase change in the liquid crystal material from the well-ordered transparent state, to a disordered, optically scattering isotropic state. Direct projection of the image thus written, produces a black line on a white background. If a smectic material is used, selective erasure can be achieved by reheating the written point, while simultaneously applying a D.C. voltage across the target. A cholesteric material can instead be used, but only page erasure is then possible; this is achieved without heat by applying a high frequency A.C. voltage across the target.

Storage time for a written image is months at room temperature. Resolution is about 70 lines per mm. and contrast is very high. Thus, although a system of this type has only been recently described as operational, it appears to have great potential for the future.

Another system has been described which uses a laser to switch a photoconductive layer which in turn causes a current to pass through the liquid crystals.[73] This can either produce a refreshed image, or, if the liquid crystals are of such a type that they store, (this can be achieved with a ten to one mixture of nematic and cholesteric materials) then page erasure, but not selective erasure, is possible. The image produced can be projected to produce a large screen display. Resolution of the liquid crystal material is greater than 50 lines per mm. Of the two liquid crystal systems just mentioned, the former would appear to be superior; but the technical problems associated with these systems have not been published in detail.

A2.2.3 Deforming films

Deforming films of either plastic or metal, as described under CRT applications in the previous section, can be used as light sensitive imaging devices by coating the surface of the deforming material with a photoconductive layer.[74] By using a photoconductor with high dark resistivity the charge deposited in response to light can be maintained for hours. To use these devices for projection displays, the projection light must strike the side of the deformed surface opposite the imaging light. Of course the deforming surface must be opaque so that the projection light does not affect the photoconductor. These devices are complicated to fabricate and have poor response at low spatial frequencies. Their potential usefulness as display devices is, therefore, doubtful.

A2.2.4 Amorphous semiconductors

Amorphous semiconductors are beginning to find their way into experimental display devices.[75] These materials are easy to deposit over large areas because the defects which occur in crystalline films are not a problem. It has been found that a pulse from a high energy infrared laser converts a localized area by means of heating from its optically transparent amorphous state to an optically diffusing polycrystalline state. When optically projected, this diffusing area produces a darkened spot on the image. Selective erasure is possible with the same laser by addressing the point with a laser pulse of different shape and energy which converts the point back to its amorphous state. The semiconducting properties of the target are also different in the amorphous and crystalline states so that scan conversion can be achieved for hard copy output or other applications. This device is very new and information on lifetime is not mentioned in the literature. Very high resolution, of the order of 300 lines per mm., can be obtained. Grey scale is, however, very limited and colour is not available.

A2.2.5 Photographic type films

Photographic type films, both photo-sensitive[76,77] and thermosensitive, (see section A2.1.4) can be used with laser systems. Ordinary light sensitive film is being used with lasers as an output medium for high quality picture transmission of up to 25,000 lines resolution.[78] As with CRT systems, non-erasable images such as this are not economically viable for interactive displays.

Permanent images have also been written on bismuth coated transparent plastic film.[77,79] The laser burns holes 5 microns or less in diameter into the metal to generate an image. A wide range of grey scale is produced by varying the size of the holes. Contrast is very high, but because of the permanent image ,the system is not practical for interactive graphics.

A2.2.6 Photochromics

Photochromic storage materials are receiving intensive investigation both for computer memory devices and for displays. Other than for the fact that they are coloured by ultraviolet light rather than by electron beams, these materials show almost the same properties as cathodochromic materials since the physical mechanism of colouring is the same in both. Many photochromic materials have been studied for display applications[80,81] and in fact one such system has recently appeared on the market. An image is written on a small piece of photochromic material; the resulting image is then optically magnified and projected. The major drawbacks of the system are its high cost, its slow drawing speed, and the image storage time which is limited to about 15 minutes.

Creating a full sized viewing surface of a photochromic material would eliminate projection problems, but would introduce fabrication difficulties. However, once suitable deflection systems have been developed, this may be a successful method of producing a large screen display with a long image storage time. Selective erasure could be achieved by using a different wavelength laser; but optical erasure of photochromic materials leads to permanent colouration of the material after relatively few cycles, following which the screen must be heated to bleach it. A colour display is probably not possible.

A2.2.7 PLZT ceramics

A series of lanthanum doped lead zirconate titanate ceramics are coming under intensive study in the field of electro-optics.[82,83] These fascinating substances, known as PLZT ceramics, are transparent and ferroelectric. They exhibit changes in their optical properties under the influence of mechanical stresses, temperature changes or electric fields. The physics of these changes is not yet fully understood. In a poled state (magnetic domains are oriented in a common direction) the material scatters light. By depoling the substance, either thermally or electrically, it can be changed to a non-scattering or transparent state. Poling or depoling also causes changes to occur in the birefringent and optical polarization properties of the material.

A laser addressed display which takes advantage of the light scattering properties of the material has been built. The laser was used to switch a photoconductive layer deposited on a thin sheet of PLZT ceramic[84,85] causing charges to be deposited at the addressed points. By choosing a proper photoconductor, it was possible to project the image without the projection light affecting the transparency of the ceramic. Selective erasure was also possible by reversing the voltage across the ceramic while a point was laser addressed. High resolution and high contrast are both possible but, because of the phase retardation properties of the ceramic, some colour distortion results and the displays have a yellow rather than a white background. However, the future of this device looks very promising.

A2.2.8 Directly viewed laser images

Full colour laser displays have been created by combining three separate lasers, with different wavelengths close to those of the primary colours, into a raster scan deflection system which is imaged onto a white surface. This system[86,87] apparently produces very good colour, with high brightness and good contrast. The major difficulty is that to produce a bright image, high powered lasers are required. To date these are both difficult and expensive to build. This problem will be alleviated as laser systems are improved and a lower resolution large screen display of this type will probably be available within a few years at a reasonable price. However, because it is a non-store display, it is not applicable to high resolution graphics.

A2.3 Electrically Addressed (Direct Address) Displays

Direct address displays are those which use electrical conductors rather than light or electron beams to cause a change in the optical properties of an addressed point or area of the display. Such systems in their simplest form are alphanumeric and seven segment numeric readouts which have a separate electrical connection to each element of the display. Although this method of addressing is ideal when a small number of points is to be addressed, present technology imposes limits on the number of separate lines which can be addressed. This limit of between 10^2 and 10^3 lines results primarily from the fact that to make the decoding logic for a large number of lines economical, it must be in integrated circuit form, while to connect large numbers of lines to an integrated circuit chip is both electrically unreliable and above certain limits, technically difficult.

In order to address more points, a matrix structure is used in electrically addressed displays.[88] A thin layer of some current or voltage activated display material is sandwiched between rows of conductors on one side and columns of conductors on the other. By applying to each of one column and one row a signal half the value required to activate the display material, full strength current or voltage is applied to one unique point on the display.

CAPABILITY	PLASMA PANELS	CATHODO-CHROMICS	LED's
Large size-100x130 cm. viewing area	no	no	yes
High Cross-talk Immunity at 512 lines	very good	poor	good
Contrast at Maximum Resolution	high	good	high
Storage Mode	yes	yes	no
Non-store Mode	yes	no	yes
Write-through Mode	no	no	---
Erasure	selective or page	page	---
Brightness	high	high	high
Grey Scale	poor	good	yes
Storage Time	until erased	seconds to days	---
Colour	being attempted	no	several descrete
Cost	moderate	moderate	very high (10^6 dollars)

Table A2.4 Electrical Address (Direct Address) Displays

DIPOLAR SUSPENSION	ELECTROPHOR-ETIC SUSPEN.	ELECTROLUMIN-ESCENT PHOS.	LIQUID CRYSTALS
no	yes	yes	yes
good	good	poor	good
high	high	good	high
no	yes	no	yes
yes	no	yes	yes
---	---	---	no
---	selective or page	---	selective or page
good	high	poor	high
some	no	good	no
---	hours	---	hours to weeks
no	no	being attempted	no
moderate to low	moderate to low	high to moderate	moderate to low

Thus, with 500 by 500 connections, which can be achieved, 2.5×10^5 points can be addressed and a display with standard television resolution results.

This description is oversimplified and in fact matrix addressing does present problems. The most serious of these is crosstalk or unwanted elements of the display being affected in the addressed row or column by the half-voltage being applied.[89] If the characteristic of the display medium is very non-linear or ideally has a switching threshold, as is the case with gas discharge displays, then the half voltage will have no effect. However, many materials respond in a linear manner to the applied signal and will exhibit some change in their optical properties with half the switching signal applied.

The second major problem is that unlike single line addressing, in a matrix system only one point or row at a time can usually be addressed. If two points in different rows and columns are addressed, then two other points will also have the full addressing signal applied to them causing erroneous information to be written. For this reason all the points which are to be written must be addressed sequentially. Either a storing display material must be used or the image must be refreshed one point or one line at a time. Refreshed images are usually only useful in a raster format, because the switching time involved in addressing discrete points is relatively long due to the high capacitance of the long conductors on the display. This severely limits the amount of data which can be presented without flicker. In a raster scan mode this problem is less severe since, with any one row or scan line enabled, several columns can be addressed simultaneously without writing unwanted points.[89] Finally, it is not easy in most cases to obtain grey scale in a matrix addressed display. Each point is either off or on and brightness is controlled by the length of time each point is addressed, although some other techniques have been demonstrated which can produce several discrete brightness levels in certain plasma displays.

A2.3.1 Plasma panels

Plasma or gas discharge displays are the best candidates thus far for matrix addressing and some are on the market.[90,91] The reason for their success is the very definite threshold voltage of a gas discharge which eliminates crosstalk problems. These units have the capabilities of random addressing, selective erasure, and page erasure. Storage is possible due to the negative resistance region in the discharge curve, i.e. the 'sustaining' voltage is lower than the threshold or turn-on voltage. Plasma displays show good brightness and contrast. For technical reasons the density of addressable points is limited to about 60 per inch[91] while the resolution of the system is limited to 512 by 512 points by the constraints listed above for matrix addressing. Research is being done on multicolour plasma displays which can be obtained by using different gases or by causing ultraviolet discharges to activate different coloured phosphors that are arranged in a manner similar to the phosphor dots in a colour television cathode ray tube.[92,93] Plasma displays can be A.C. or D.C. driven and of a variety of structures.[94-98] With television applications in mind, self-scanning methods have been devised in which the elements of the system are addressed sequentially in a raster format by one of several methods. The result is that only a few lines need be connected between the display and the control logic, allowing more economical fabrication of the device. However, this limits to a raster pattern the format of the data which can be entered.

The high voltages which must be switched to operate plasma displays, together with their high power consumption, make the electronics difficult to fabricate at a reasonable cost. This makes them a poor candidate for displays as other lower voltage materials are now being developed. Reference 94 in the bibliography contains ten papers which provide information and references on all aspects of plasma displays.

A2.3.2 Cathodochromics

Cathodochromic materials can be coloured by electrically injecting electrons either via a semiconductor layer or with a high voltage applied to a point electrode.[99] The former method was suggested by Robillard for a matrix display using KCl.[100] The usefulness of such a system has not, however, been proven. It is unlikely to provide a suitable display because these materials show a linear integrating tendency to colouration with applied signal so that half addressed points would be affected.

A2.3.3 Light emitting diodes

In the distant future, it has been predicted that light emitting diode displays will probably hold a large share of the display market, due to major advances in the fabrication and properties of these electroluminescent materials[101] but at the present time they present several difficulties for systems of appreciable size.[102-104] The luminous efficiency of red LED's is about four per cent of the theoretical maximum value while green and amber efficiencies are still far below that figure. These efficiencies will no doubt be improved but,at the present time,a display of adequate brightness for daylight viewing using red LED's would dissipate about 500 watts per square foot, an unacceptably high value. However, the high brightness of LED's coupled with their non-linear switching characteristics and the possibility of image storage[105] makes them good candidates for matrix addressed systems and work is continuing in this field. Units as large as 15 by 15 cm. with a resolution of 128 by 128 elements have been fabricated. The most ambitious project reported to date is being done for the U.S. armed forces. A 1000 by 1000 point resolution, three colour (red, green, amber) display with grey scale capability will be fabricated.[106]

A2.3.4 Dipolar suspensions

A matrix addressed display has been described which uses a liquid suspension of a dipolar material.[107] An addressing voltage orients the dipolar particles to create a transparent point in the normally diffusing suspension. Contrast is high, the material exhibits the non-linear characteristics required for matrix addressing and the transparent spot created by addressing a point can be much smaller in diameter than the thickness of the suspension because of an effect called the 'Iris Effect'. The spot diameter can be varied by changing the supply voltage creating it. High resolution of 10^2 to 10^3 lines per mm. can be obtained with voltages of from one to ten volts. Switching speed is claimed to be fast enough for real time displays.

A2.3.5 Electrophoretic panel

A device called an electrophoretic image display panel (EPID) uses a sandwiched suspension of very fine pigment particles which become charged and are attracted by either a positive or negative electric field (the electrophoretic phenomenon).[108] When a point is addressed, the particles migrate either to or away from the viewing surface, creating a change in the colour of the surface at that point. Switching time for this device is from ten to twenty milliseconds and contrast is high. The material exhibits a storage effect because the Van der Waals attractive forces hold the particles to the display surface after the voltage is shut off. Switching voltages are too high for IC technology, from 50 to 150 volts, and lifetime at present is only 3000 hours.

A2.3.6 Electroluminescent panels

Electroluminescent phosphors have been known for thirty years and are one of the first materials suggested for flat panel matrix addressed television. However, technical problems stubbornly refuse to yield to the efforts of researchers. Some of these are the approximately linear response of the phosphors which cause crosstalk in matrix addressed displays, low brightness, early fatigue, and high addressing voltages. A device which overcomes the linearity problem of the phosphors and provides storage has been built.[109] Work is continuing on systems and many of their shortcomings have been corrected to some extent with new and improved phosphor materials.[110,111] Experimental television panels have been built[112,113] but it is probable that progress in other competing technologies for matrix addressed displays will prevent electroluminescent phosphor devices from reaching the commercial market.

A2.3.7 Liquid crystals

Liquid crystals show great promise for matrix addressed displays.[114-121] They can be operated with negligible power in the field effect mode,[117] they switch at low voltages permitting IC technology to be used for addressing, they can be made to store an image; and finally the liquid crystal materials are very inexpensive. Either A.C. or D.C. drive can be used. Fatigue has been a problem, but with A.C. drive this has been sufficiently reduced to make life time suitable for commercial applications. Selective erasure is not yet possible and neither adequate colour nor grey scale can be foreseen in the immediate future. Nevertheless, some displays of this type can be expected in the next few years to compete with plasma display panels. The use of liquid crystals in a real time non-store mode is hampered by the slow switching speed of the material which is in the order of several milliseconds.

A2.4 Magnetic Adressed Bubble Systems

Bubble devices represent a technology which does not resemble any other in the field of displays.[122-128] The basic structure of the bubble device is a thin film of ferromagnetic material. When a weak external magnetic field is applied perpendicularly to the film, the domains form themselves into chains which have an appearance similar to finger-prints.[124] As the magnetic field strength is increased these chains break up and form cylindrical bubbles which are oriented perpendicularly to the plane of the film so that viewed from the top they appear as circles. Increasing the field makes the bubbles smaller, while decreasing it makes them grow. Because these bubbles cause optical changes in the properties of the material, they can be made visible.

PROPERTY	QUALITY
Viewing Area	Less than ten $cm.^2$ at present, larger areas will be possible
Resolution	Up to 100 lines per mm.
Contrast	fair, high for liquids
Storage	Yes
Write and Erase	Selective, page, or specified symbols
Grey Scale	Created by bubble size and number of bubbles
Cost	ultimately could be moderate to low
Colour	May be possible in multilayer devices
Other Capabilities	Data manipulation without rewriting the display from an external memory

Table A2.5 Properties of Magnetic Bubble Displays.

Originally, bubble devices were fabricated in single crystal garnet films. The major problem with single crystals is that flaws, which inevitably exist in the crystal, affect the properties of the film. Later researchers found that certain amorphous films and other materials[125] could be fabricated by simple sputtering techniques, with properties equally as good as single crystals for the operation of bubble devices. Since amorphous films do not possess the faults inherent in crystals, the limitation of the area available for building these systems has been relaxed appreciably.

Soon after the ability to create these bubbles was learned, methods were developed to move them around. In the single crystal devices, metallized areas were deposited on the crystal surface. One pattern which is commonly used is a string of triangles all pointing in one direction. It is found that by decreasing the magnetic field so that the bubble overlaps two triangles, and then increasing the field again to shrink the bubble, it will move from one triangle to another. In this way a pulsating field will move bubbles along in a shift register fashion. Special patterns will create bubbles or switch bubbles from one path to another on changing the current in small conductors beneath these switching elements. Other devices called 'busters' will destroy bubbles. It can be seen that with these facilities it would be possible to create logic elements, such as adders or gates, directly on the bubble film.

It was found that the metallization was not needed to guide the bubbles because by etching the patterns into the film, exactly the same effect is created.[126] Guide rails can be etched along the edges of the bubble path to restrict the amount of spreading sideways. Bubbles can then be stretched over the length of several triangles so that larger areas are covered. The larger areas served as segments in an experimental seven segment display which was fabricated recently.[127]

More recently, systems have been built in which liquids rather than solids are the medium in which bubbles are generated.[128] As these bubbles are larger and more easily visible, they could ultimately be the method through which displays are realized.

Although several attempts have been made to apply bubble systems to graphic displays, it may be years before this type of system could be commercially viable. Nevertheless, the potential of a display with logic, write, and erase functions could very well revolutionize the concepts of graphic data manipulation.

APPENDIX THREE

SUPPORTIVE EXPERIMENTAL WORK

During the course of the research, difficulties were encountered which have not been described because they were overcome, bypassed, or resulted in a particular line of attack being abandonned. Some of these investigations are briefly documented in this Appendix.

A3.1 Fabrication of Targets

A3.1.1 Powdered targets

There were initially no facilities available to reproduce the fabrication of evaporated KCl targets described in the published literature. It was felt that, at least for initial dark trace tests, settled powder targets would be adequate. However, it was difficult to find a method of causing the KCl powder to adhere to the substrate without using binders which might affect its cathodochromic properties. After some experimentation, it was found that a mixture of 91% isopropyl alchohol and 9% water would allow the KCl to settle onto the target without being dissolved. The surfaces of the particles were wetted only enough to cause them to adhere to each other and to the substrate after targets were dried.

In commercial settled powder systems, the liquid through which the powder has settled, is decanted very slowly over a period of hours. This is done to avoid disturbing the material which has settled onto the target. Attempts to do this in the laboratory, without the sophisticated apparatus, were not successful. The problem was overcome by performing the settling of the powder under a fume hood, then warming the container so that the alcohol and water were evaporated. After the target had completely dried, it could be handled without any special precautions.

After this method of fabricating and colouring powdered KCl targets had been successfully accomplished, the same procedures were used to make targets with other cathodochromic materials. One of these materials was potash, which is a mixture of KCl and NaCl with various impurities. Samples of this material, when irradiated for long periods of time, produced an almost permanent, and very dense, colouration. Some samples required heating to above 150°C to cause bleaching of this colouration. Although its image retention properties were superb, it was several times less sensitive to colouration than was KCl. Thus it was not considered as a useful target material.

In addition to fabricating settled powder targets, attempts were made to grow polycrystalline targets by evaporating the water from an aqueous solution of KCl. The results were unsatisfactory, as the KCl tended to form large localized deposits, rather than the desired smooth polycrystalline surface.

A3.1.2 Evaporated targets

As soon as the necessary facilities and tools became available, transparent and diffuse evaporated KCl targets were fabricated. It was found that the quantity of KCl deposited was important. The first layer deposited, up to approximately five microns, did not appear to have any crystalline structure, and was transparent. It was observed that by using very rapid deposition, the transparent layer could be made as thick as 20 microns. However, as further KCl was deposited, the target became milky, presumably as a microcrystalline structure developed.

When transparent targets were exposed to a humid atmosphere, they became milky in a few seconds as crystals formed on the surface of the KCl.

A3.1.3 Other transparent targets

Most methods of fabricating transparent targets, with the exception of vacuum deposition, met with limited success. One technique involved melting KCl onto Vycor glass. (Normal glasses had a lower melting point than that of KCl.) Even this high melting point glass became damaged to some extent by the high temperatures used.

In another experiment, pressed discs of KCl were fabricated. Many trials were required to obtain a disk which was transparent over the majority of its surface. These disks were very fragile because the press used was not capable of applying the full pressure needed. Although the discs would not have been adequate for any useful device, nevertheless they were adequate for experimental purposes.

A3.2 Tin Oxide and Aluminum Conductors

Before fabrication of each evaporated target, it was intended to deposit a layer of tin oxide to serve as a transparent conductor. While awaiting details of other experimenters work, several tin oxide evaporation techniques were tried in the vacuum system; none of these were successful. Ultimately, a reflective coating of Aluminum was substituted for the tin oxide. Although this required some changes in the optics configurations used for projecting the dark trace images, the reflective technique was successful, and probably resulted in higher contrast images than could have been obtained from transparent projection methods.

A3.3 Electron Gun

It was not possible to purchase a suitable electron gun for the experimental work. An experimental gun was therefore made from a discarded cathode ray tube. Since the oxide coated cathode in such a device is destroyed upon exposure to the atmosphere, it was necessary to replace it with a tungsten filament. Electron microscope filaments were found to be satisfactory, but required very careful alignment. A special mount was designed and fabricated which would allow both lateral and vertical translation of the filament. The alignment was accomplished by using a thin copper wire and and ohmeter as a probe, to determine the location of the filament inside the control grid cage.

Although this method of alignment yielded acceptable results, it was very time consuming, as the filaments lasted for only a few days. In addition, the alignment could never be precisely repeated. Thus, when a new filament was installed, it became necessary to recalibrate the grid bias and beam current circuitry.

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