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SURVEY OF MULTI-FUNCTION DISPLAY AND CONTROL TECHNOLOGY

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ABSTRACT

The NASA Orbiter spacecraft incorporates a complex array of systems, displays and controls. The incorporation of discrete dedicated controls into a multi-function display and control system (MFDCS) offers the potential for savings in weight, power, panel space and crew training time. In this report, the technology applicable to the development of a MFDCS for Orbiter application is surveyed. The report is concerned primarily with technology thought to be applicable presently or in the next five years. Areas discussed include display media, data handling and processing, controls and operator interactions and the human factors considerations which are involved in a MFDCS design. Several examples of applicable MFDCS technology are described.

1.0 INTRODUCTION

This report describes the procedures followed and results obtained by Boeing in performing Task 1 (Survey of Existing Technology) for NASA contract NAS9-16445, "Development of Preliminary Design Concept for Multi-function Display and Control System for Orbiter Crew Station".

1.1 Purpose

The purpose of this report is to provide a review and an assessment of current and relatively near term technology developments which might be applicable to updating the capabilities of the Orbiter display and control system using multi-function display and control concepts. The report will serve as a base from which technology particularly applicable to the Orbiter OMS and EPDS systems will be configured into preliminary design concepts for a future display and control system update.

1.2 Scope

Technology surveyed in this report includes both applicable hardware and the human factors research and technology necessary to effectively integrate the hardware into display and control systems, which will provide a more efficient operator interface with the system. The survey concentrates on presently available technology broader than might be applicable to any specific shuttle system. From this broader base, applications to specific Orbiter systems will be selected.

1.3 Search Process

Display and control (D & C) technology contains both rapidly and more slowly varying components. Hardware elements are particularly subject to short term changes with potentially applicable new devices being introduced as a product or described in research and development literature each week. The time span over which a D & C system is designed, developed and intergrated into a system is typically several years or more. Thus, an assessment of applicable technology for a display and control system should look ahead to the probable state of

technology near the implementation of the designed D & C system. In turn, the design should provide for inclusion of useful new technology without major design rework.

The search process for the survey of technology concentrates on relatively recent sources of information. These include current literature such as research reports, manufacturers' publications and trade journals. Conversations with selected personnel are also used to check on the latest available updates to the literature where developments are progressing rapidly. Considerable applicable development work is being carried on in-house at Boeing and information on these efforts are used to supplement the data available from government, industry and academic sources. By looking at currently available technology and ongoing research and development, some estimates of the near term direction in the various display and control technologies are made.

1.4 The Multi-function Display and Control Concept

The term multi-function display/control system (MFDCS) applies to any display/control system in which there are more displayed functions than there are displays or more controlled functions than there are controls. Hence, in a MFDCS at least some of the displays or controls are shared by more than one function, rather than being dedicated to a single function.

A very simple example of multi-function controls is found on scientific pocket calculators. On most of these devices, some keys are multi-function in that they control two different functions. The secondary function is usually identified by a label beside the key, or in a different color, and is typically accessed by first pressing a key labled "F" or "2nd F".

Experience with MFDCS's suggests that these seldom consist only of displays and controls that have multiple functions. Instead, almost all systems include a few functions implemented as dedicated controls because they are accessed so frequently or because they are so critical that they must always be immediately available. In the pocket calculator example just cited, the "F" key used to access the secondary functions is almost always a dedicated control.

2.0 RELEVANT TECHNOLOGY DETERMINATION

This section of the report describes the range of technology to be assessed in conjunction with the Orbiter D & C system and the definition of the important issues within the various areas of technology.

2.1 Relevance Criteria

The Orbiter Display and Control system extends from the hardware actuating flight control surfaces, valves, etc. to the switches, display and control handles which interface with the Orbiter operators. This survey has been limited to that portion of the display and control system associated with data handling once the various readings from the sensors, actuators, valves, etc. are received on the main data bus. This information defines one of the relevance criteria for inclusion of technology in the survey. Additional limitations on hardware considered will exclude those technologies which are clearly not suited to Orbiter application.

Applications of display and control modifications to the Orbiter are limited by a variety of mechanical, electrical and functional parameters. Mechanical factors include available panel space, depth behind the panel, weight, g-load, vibration response and heating and cooling requirements. For example, large area displays are not considered in this survey because of space limitations. Similarly, display or control components offering a space or weight savings would be of interest for Orbiter applications.

Electrical factors considered include power, voltage and current requirements, signal handling interfaces and data rate capabilities. The range of electrical display equipment surveyed for example, consists of electro-optical components with a reasonably rapid response time and a moderate to large data display capability. Electro-mechanical devices have not been included.

Functional parameters include operator interactions with displays and controls, reliability, difficulty of implementation and impact on other Orbiter systems.

2.2 Display and Control System Description

A typical computer based display and control (D & C) system can be subdivided into several separate areas of consideration. The major divisions are shown in Figure 2-1. In this survey, the sensors and actuators have not been considered a part of the D & C system eligible for modification or replacement. Current displays in the Orbiter include electro-mechanical and electro-optical indicators. Only the electro-optical display devices are surveyed in this report as the use of these displays is gradually superceding the electro-mechanical displays.

Processing is taken to include the actual data processing, transmission of the data via data bus and storage of the processed data in processor or mass storage memory. Another section is devoted to display system controls and operator interactions. The typical discrete operator controls (e.g. single function switches, trackballs, etc.) are well established and, although they often form a part of proposed multi-function D & C systems, will not be considered here. Emphasis is placed on available and projected multi-function controls and interaction techniques.

2.3 Technology Overview

Technology applicable to multi-function display and control systems is becoming quite varied with the introduction of faster processing, new display forms and continuing advancements in the integration speed and miniaturization of electronics. In this report, the technology is surveyed first in terms of individual subareas applicable to multi-function systems. These are the areas where developments are occurring which will impact future multi-function designs and systems. A number of new developments in both cathode ray tubes and flat panel displays make possible new concepts with respect to color, resolution, package size, weight and power consumption.

Processing and data handling capabilities are expanding rapidly with the advent of faster and less expensive processors. Electronics modules formerly requiring many components and considerable design are now appearing as single chip devices. This trend is accompanied by advances in data bus technology as well as considerable innovation in mass storage technology. Solid state memory chips

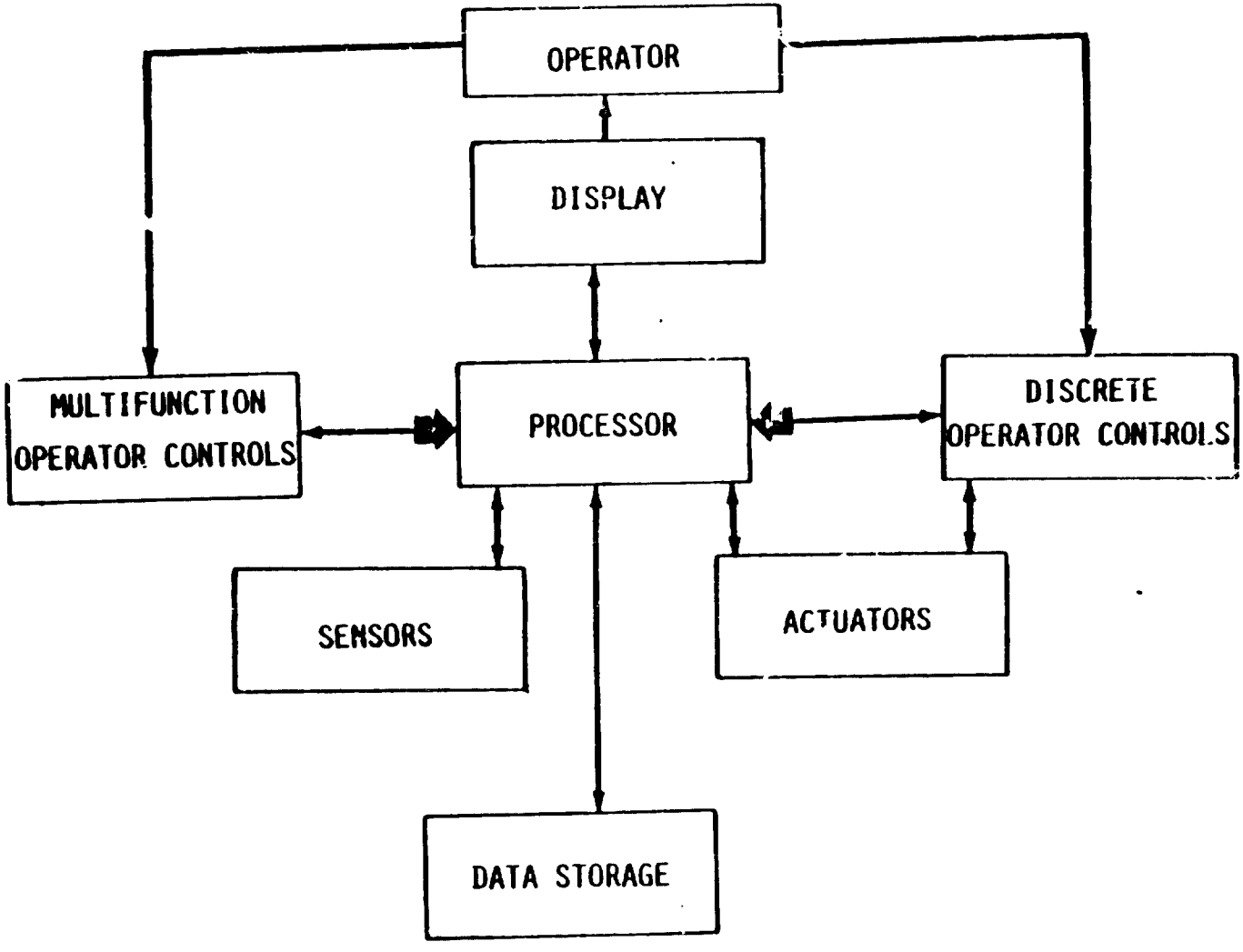

Figure 2-1: TYPICAL DISPLAY & CONTROL SYSTEM

are continually increasing their capacity and magnetic and/or optical disc storage is currently available at relatively low cost even in the consumer markets.

Controls for multi-function systems have become more versatile with the development of programmable legend switches, dot matrix displays and touch panel overlays. Voice interaction offers another new area of operator system interaction.

Secondly, the technology is surveyed in terms of applications of the individual subareas to multi-function systems. Many of these systems represent, at best, only designs or partial implementations of multi-function systems. However, taken as a whole, a broad picture of multi-function systems completed, designed or partially implemented can be obtained. Currently only limited information on the performance of multi-function systems is available. As more multi-function systems are implemented, a greater body of knowledge on both the performance and design of these systems will be available.

2.4 Issues Within Technologies

Current technology offers a variety of options for the implementation of multi-function display and control systems. The application of the technology to the Orbiter display and control system involves both hardware and human factors considerations. Both must be considered in the design of a successful system. The following subsections outline some general technology considerations. Specific considerations such as resolution, speed, etc. will be dependent on the particular Orbiter system under study.

2.4.1 Hardware

A prime factor in the design of a multi-function display and control system on the Orbiter is reliability. Current hardware includes multiple redundancy on critical systems to ensure crew safety and maintain operability. Typical systems employ triple or quadruple redundancy. The projected Orbiter mission lengths and lack of readily available maintenance facilities require a display and control system to provide for crew capability to monitor, diagnose, reconfigure and/or

repair malfunctions on station. At a projected cost of $30 million/flight the economic considerations of a mission aborting or curtailing problem can be quite considerable.

Mission duration, spacecraft complexity and payload maximization place a premium on the limitation of weight, volume, panel space and power requirements for Orbiter equipment. Considerable effort has already been made to lighten the Orbiter structure, particularly on the second Orbiter under construction (Reference 2-1). With a cost per pound of orbited payload weight on the order of $500, any unnecessary weight becomes quite expensive. Since weight in the cockpit area must be counterweighted in the aft area of the Orbiter by twice the weight, each extra cockpit pound of weight implies a $1,500/flight penalty. In a similar fashion, excess power consumption increases the load on the Orbiter electrical and cooling systems, possibly requiring heavier, higher capacity wiring and fuel cell supply capability.

Volume and panel space are, to a large extent, well defined in the Orbiter, hence any implementation of a multi-function display and control system will require conformance with the currently available envelope of volume and panel space.

2.5 Technology Study Application

During the remainder of this study contract, multi-function display and control technology of the type described here will be applied to two Orbiter systems. These are the Orbital Maneuvering System (OMS) and the Electrical Power Distribution and Control System (EPDCS).

The OMS provides the thrust for Orbiter orbit insertion, orbit modification, rendezvous and deorbit. It consists of two gimballed rocket engines, a propellent pressurization subsystem and a propellant tank and distribution subsystem. Operator control and monitoring is implemented through several discrete switches and displays plus the CRT and keyboard. These are located on eight panels within the Orbiter crew station.

The EPDCS distributes direct current (dc) and generates and distributes alternating current (ac) to the electrical equipment in the Orbiter. Distribution is by means of five types of redundant buses. Operator control and monitoring occurs by means of about 49 dedicated controls and displays located on five panels within the Orbiter crew station. Performance of the EPDCS is also monitored on the Orbiter CRT displays.

3.0 DISPLAY MEDIA

Displays for use in the Orbiter display and control system will be limited in available panel space and in depth. Two basic classes of display are considered in this survey. Cathode ray tubes (CRT's) form one basic class and are currently used in the Orbiter. Flat panel displays constitute the other basic class and include such displays as light emitting diodes (LED's), liquid crystal displays (LCD's), electro-luminescense (EL), vacuum fluorescense (VF), gas discharge (GD), electrochromic (EC) and electrophoretic (EP) displays.

CRT displays have traditionally offered the advantages of wide availability, good resolution, flexible display format, rapid response, simple interfacing and relatively low cost. Disadvantages of the CRT include a relatively bulky package (due to tube depth), non-graceful degradation, high voltage requirements, and relatively short lifetimes. Various flat panel displays have been and are being developed to overcome these disadvantages. The flat panel displays are currently coming into use in several limited applications where weight, volume and or power are at a premium. Low resolution, limited colors and complicated pixel addressing remain as problems however.

3.1 Cathode Ray Tubes

Perhaps the most important recent trend in CRT displays has been increased use of high resolution multi-color tubes for the display of both alphanumeric and graphic information. Beam penetration and shadow mask CRT's are the primary varieties of tubes in use to achieve multiple color formats.

3.1.1 Beam Penetration Tubes

Beam penetration tubes rely on a multi-layer phosphor on the CRT face to produce multiple colors. The color produced is controlled by the acceleration voltage used on the electrons emitted by the electron gun. Figure 3.1-1 shows a schematic diagram of the beam penetration screen. A low acceleration voltage (~10kv) excites the red phosphor. A higher voltage excites both the red and green phosphor. Maximum voltage (~18kv) causes electrons to penetrate the red phosphor. Thus, by varying the acceleration voltage, colors from red to green in the spectrum can be produced.

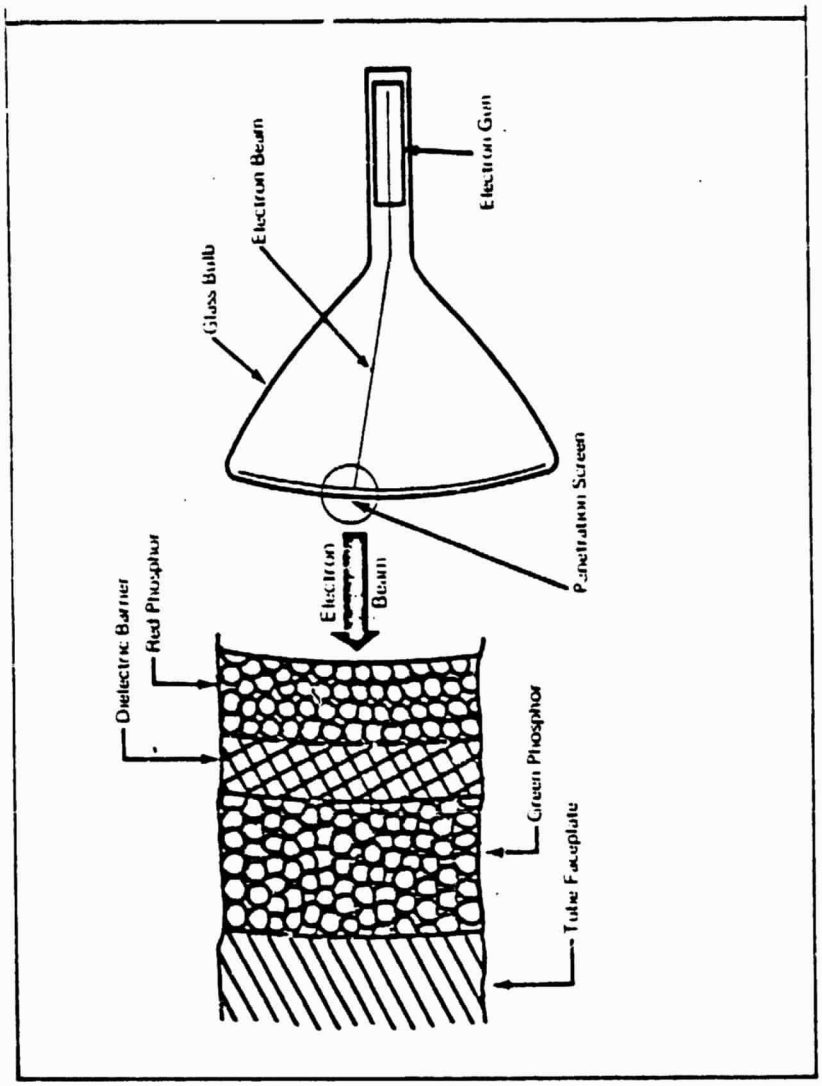

Figure 3.1-1: COLOR PENETRATION TUBE (SIMPLIFIED)

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This type of tube is typically used in a stroke-writing mode and offers the advantages of high resolution, single electron gun struction, high writing speed and clear graphics generation. Raster capability is also available if desired. Disadvantages of this tube type include the lack of a blue phosphor, and a resultant lack of full color display capability, and the necessity to rewrite data on the screen at more than one energy to obtain a full range of color hues between red and green. For colors requiring rewrites at more than one energy, the color registration has also been a problem.

3.1.2 Shadow Mask Tubes

Shadow mask CRT's have most often been used in raster scan displays. Considerable progress has recently been made in tube performance, environmental ruggedization and projected tube lifetimes. These improvements and the full color capability of the shadow mask CRT have led to usage in cockpit displays in place of electro-mechanical instrumentation.

A large (19") militarized shadowmask CRT has recently been developed for the aircraft environment by Hazeltine. These units are designed for console displays such as AWACS installations, but provide an indication of the range of operating parameters satisfied by currently available CRT's. Some specifications for the Hazeltine tube are shown in Figure 3.1-2 (Reference 3-1).

Shadowmask CRT's can also be used in a stroke-writing configuration, although a number of potential problems exist due to the discrete nature of the color traids on the tube screen. Shadowmask tubes produced by Collins Radio are currently being used for cockpit instrumentation in the Boeing 757/767 aircraft. This application uses the tubes in both a stroke-writer and raster scan mode. The stroke-writer mode is used for lines and symbols in the various colors while the raster scan mode is used to fill in areas such as the display of weather radar data. These tubes represent a significant advancement in performance with a specified lifetime of 15,000 hours and sufficient brightness to be used in the aircraft cockpit while operating in an 8,000 ft.-C. environment. Seven colors are used in the various displays.

Display Area:	38 X 28cm
Display Pixels:	1280 X 1024
Colors:	R-G-B (4 bit gray scale)
Brightness:	> 40fL (white)
Spot Size:	.050cm
Frame Rate:	30 - 60 frames/second
CRT Type:	Shadow mask, high resolution (.030cm triad spacing)

Figure 3.1-2: HAZELTINE CRT PARAMETERS

3.1.3 Monochrome Tubes

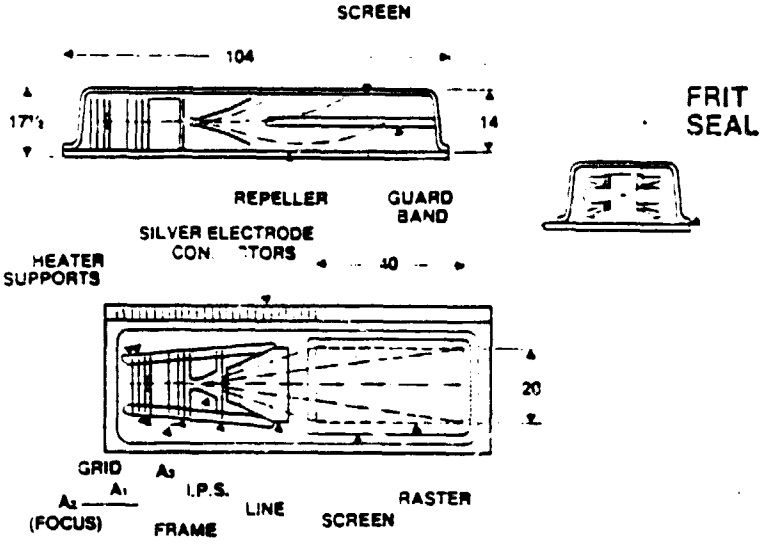
Monochrome tubes are being incorporated into small, high resolution display modules for use as graphics and text display media. These units offer features such as built-in character generation, high resolution dot addressing capability (i.e. 2048 X 2048) and programmable intensity levels. Modules of this type are typically set up for direct interfacing to a computer or microprocessor data source. A possible drawback to some of these units is the use of an electrostatic deflection system which has been shown to exhibit poor beam stability in certain vibration environments. (Reference 3-2).

3.1.4 New CRT Tube Designs

Of the drawbacks to the CRT tube for flight instrumentation, a major problem is the depth of space required for a CRT installation. This depth is typically comparable to the height and width of the tube face. A new tube design by Sinclair Research is currently transitioning from the development to production of a "flat" CRT (Reference 3-3). The new design uses an electron gun mounted at the side of the tube as shown in Figure 3.1-3 which also provides a comparison of typical operating parameters for the "flat" CRT and a conventional monochrome tube. The savings in depth is considerable although the electron gun area would use up potentially valuable panel space in a cockpit configuration.

3.2 Flat Panel Displays

Flat panel displays have been developed with a number of objectives in mind. These include shallow depth, low power, solid state construction, long life, low cost and low weight. Most of these objectives are measured relative to the CRT as the dominant electronic display medium. No flat panel displays have yet appeared which equal the wide range of performance of CRT tubes. However, flat panel devices are being used in special purpose applications not suited to or not requiring a CRT. Perhaps the most widespread use of flat panel displays has been in the consumer areas such as clocks, watches, calculators and electronic games. The dominant display forms have been light emitting diodes (LED's) and liquid crystal displays (LCD's). In the industrial, commercial and military sectors, gas discharge (GD) and vacuum flourescent (VF)



(ARBITRARY UNITS)

	MAGNETIC	ELECTROSTATIC	SINCLAIR TUBE
VOLUME	2	2.5	1
DEFLECTION POWER	10	4	1
PARTS COUNT	2	3	1
GLASSWARE	COMPLEX	COMPLEX	SIMPLE
BRIGHTNESS	1	1	3
RESOLUTION	1	1	1
SCALING LAW	ADVERSE	ADVERSE	FAVOURABLE

COMPARISON OF SINCLAIR TUBE WITH CONVENTIONAL ELECTROSTATIC AND MAGNETIC TUBES

Figure 3.1-3: SINCLAIR 2-INCH FLAT CRT

displays have found a number of applications. Electroluminescent (EL) panels are currently under heavy investigation although their market availability is very limited. Other flat panel displays being investigated include electrochromic and electrophoretic displays.

Flat panel displays have been most often used for limited numbers of alphanumeric characters and the panels are typically arranged in either segmented or dot matrix formats. Segmented formats have been the most prevalent form to date, however, the capability for presentation of graphics information, non-standard symbols or more than one font size makes the fully populated dot matrix format an attractive choice for many display uses.

3.2.1 LED Displays

The use of LED's for alphanumeric displays is widespread in the instrumentation and consumer electronics areas. Prime attributes of the LED include small volume, low voltage requirements, solid state construction, ruggedness and long operating lifetime. Principal drawbacks have been the high cost of constructing large arrays of LED's and the achievement of the drive power required to achieve readable contrast ratios in a high ambient light environment without excessive heat buildup. This survey concentrates on the development of dot matrix displays suitable for the display of both alphanumeric and graphics information and on relatively new technology associated with LED production. Smaller numbers of characters (i.e. 3 - 4 digits, segmented) are available routinely from a number of manufacturers.

Considerable development work on dot matrix LED arrays has been done under the direction of Air Force Wright Aeronautics Laboraties (AFWAL) in conjunction with Optotek and Litton of Canada. Interest has centered on two areas: 1) medium resolution (40 - 64 lines/inch) displays for use in programmable legend switches and 2) high resolution (>100 lines/inch) displays for use in video scene generation. Work to this point has concentrated on green (GaP) diodes designed for high efficiency to provide cockpit visibility in sunlight with reasonable power consumption. A goal has been the development of processes and yields to manufacture arrays one inch square or larger from a single silicon wafer. These one inch squares have been designed to be edge abutable for assembly into larger arrays (References 3-4, 3-5, 3-6). A prototype unit complete with drive electronics has been constructed and tested for use.

The other approach to building LED arrays is construction by attaching single LED's to a substrate. To achieve uniformity, the LED's are matched for luminance vs drive current before attachment to the substrate. Litton of Canada has developed green LED panels for AFWAL using this construction. Sanyo Electric Company, Ltd. has constructed a green LED 240 x 320 element array (Reference 3-7) for use as a television display. Sanyo has also constructed a smaller 64 x 96 element array where each element is comprised of both a red and a green LED in a single chip. This unit has a resolution of 25 lines/inch and can display colors from red to green in the spectrum.

Optotek of Canada (Reference 3-8) has concluded that the single diode construction may be most cost effective for low to medium resolution (<64 lines/inch) with the monolithic diode arrays being more cost effective for high resolution (>100 lines/inch) displays. Continuing efforts are being applied to improve the efficiency of both the red and green diodes.

A missing element in the LED capabilities is the availability of a blue LED. Blue LED's have been produced experimentally, but are inefficient relative to green and red LED's. They have not been incorporated into display panels. Siemens (Reference 3-9) is currently producing blue LED's for specialized nuclear reactor and medical uses at very high cost.

3.2.2 Liquid Crystal Displays (LCD's)

Liquid crystal displays have been under development as a display device for over a decade. These displays have considerable potential for applications in which their passive characteristics and low power consumption are desirable features. LCD's are typically manufactured in a reflective, transmissive or transflective mode. Reflective LCD's are visible through reflection of ambient light. Transmissive LCD's require a backlighting source to achieve visibility and hence require more power in high ambient light and are equipped with an electroluminescent layer to provide light in low ambient light conditions.

The dominant current LCD form is the twisted-nematic display. These displays have found wide application in watches, electronic calculators, games and in test equipment such as multimeters. Most of the available displays have been in a several digit

alphanumeric seven-segment format. Recently, the twisted nematic displays have been manufactured in dot matrix formats for the representation of 5 x 7 characters. One current model will display four lines of 40 ASCII characters. Character height is 5.5mm (Reference 3-10). Power consumption is 400mW. A corresponding power for a comparable number of LED characters is 26W (Reference 3-11). LCD's are relatively simple to manufacture since the whole panel is prepared as a unit.

Several trends are occurring in the LCD industry. Resolution and contrast ratio are subjects of continuing improvement. The twisted nematic displays show a decrease in contrast ratio with increased multiplexing. As the number of multiplexed rows increases the difference between the on and off voltages on the displays narrows and the transition becomes less clear. Tests on a General Electric LCD indicate a limit on multiplexibility of 7 - 8 lines for a contrast ratio of 3 and a reasonable field of view (Reference 3-12). Field of view is an area of continuing limitation in multiplexed twisted nematic LCD's.

The recent introduction of dichroic LCD's has offered the option of a wide field of view at a good contrast ratio. In addition, the use of colored dyes for the LCD fluid gives color options from blue to red. Only a single color is available for each unit at this time. Unfortunately the dichroic LCD's do not multiplex well. Approximately two multiplexed rows appears to be the current limit.

Perhaps the most significant trend in improving LCD displays is the integration of transistors with each of the LCD pixels. The transistors are used to maintain voltage on the pixels between refresh cycles. Thus the reduction in contrast ratio due to multiplexing does not occur. The concept is being worked on in both the United States and Japan.

In the United States, Panelvision (Reference 3-13) anticipates distribution of a prototype LCD unit with an active area of 10cm x 6.6cm comprised of 191 columns x 128 rows in early 1982. A second 400 column x 250 row unit is also planned. The first unit will have 48 lines of resolution while the second unit will have 67. Figure 3.2-1 shows a graphic data set portrayed on one of the 191 X 128 pixel displays. In Japan, Toshiba is developing a 220 x 240 pixel LCD television panel using similar methods (Reference 3-14).

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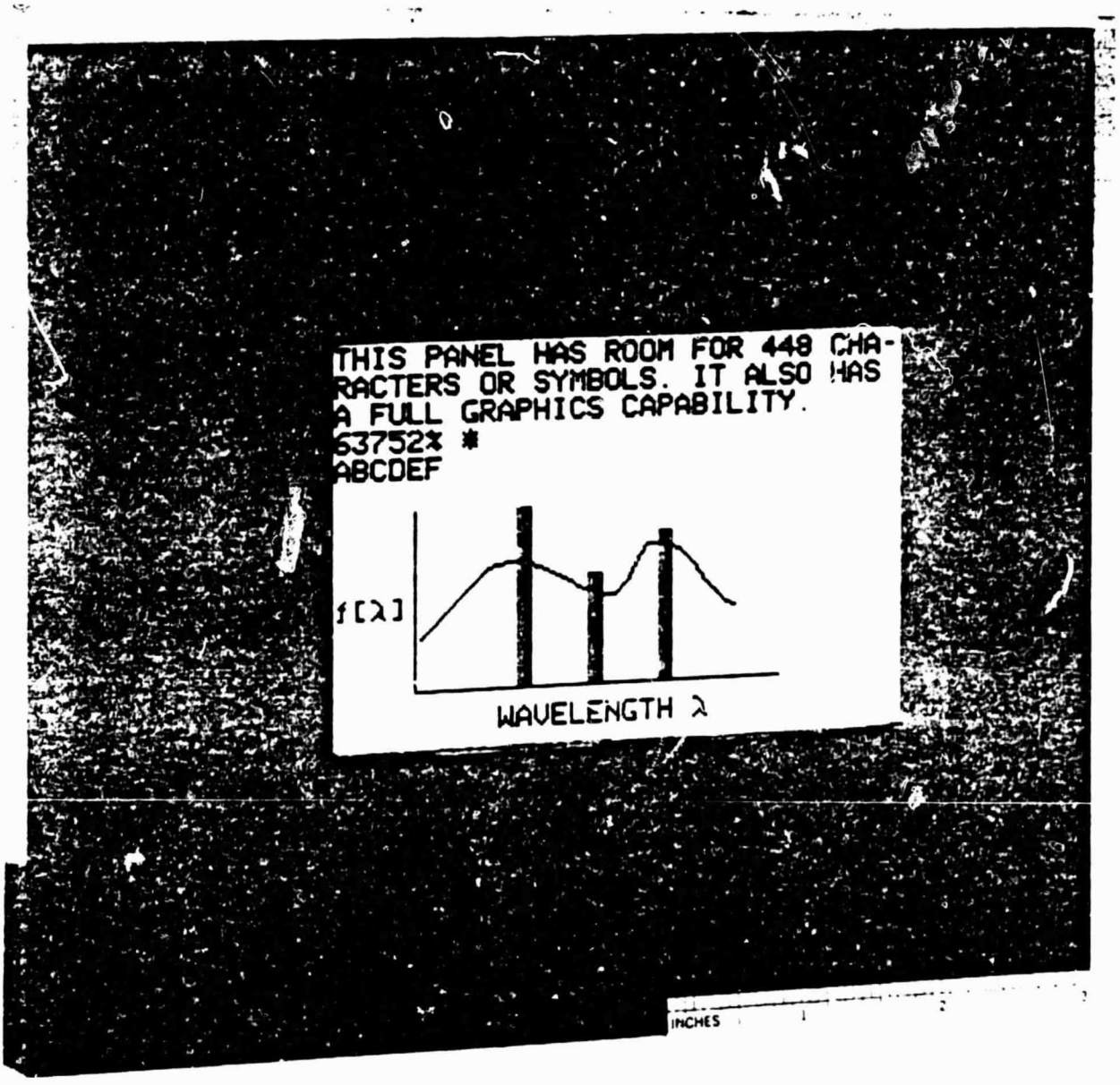

PANELVISION LIQUID CRYSTAL DISPLAY MOUNTED ON CIRCUIT BOARD
OVERALL DIMENSIONS 7-1/4" x 6-1/2" x 3/8"
ACTIVE AREA 4" x 2-5/8"

Figure 3.2-1: LCD PANEL WITH INTEGRATED DRIVERS

Another technique has been developed by Kylex. This method uses transitions in the operating mode of the LCD fluid as a function of temperature to "freeze" the information impressed on the individual pixels. This permits a much higher number of lines to be multiplexed by giving the LCD panel an inherent memory. A Kylex panel has been demonstrated in a 15cm x 17.5cm, 512 x 576 pixel format (Reference 3-15).

3.2.3 Electroluminscent (EL) Displays

Electroluminescence has been regarded with considerable interest in its various forms since the 1960's. Primary potential advantages are lower power consumption than LED displays and a solid state large area construction technique. Short lifetimes and lower luminance have been continuing problems. In recent years, considerable development effort has been devoted to thin film electroluminescent (TFEL) displays. Sharp has introduced dot matrix panels of moderate luminance with good resolution and quoted lifetimes to half brightness of 10 years (Reference 3-16). The introduction of black contrast enhancing layers has greatly improved the readability of TFEL displays in high ambient light environments.

A major portion of recent development effort has been supported by the military services, particularly by the U.S. Army in a program under Dr. Elliot Schlam at ERADCOM, Ft. Monmouth, N.J. Development efforts have been supported in the production of large panels, high contrast ratios, integrated circuit drivers and power supplies. TFEL panels have been developed as both a static display medium and as a medium for video display. Much of the commercial development has been directed towards the goal of a flat screen television. Several experimental models of video usage have been demonstrated (Reference 3-16). As yet, commercial production of small TFEL flat panel television sets is probably several years away.

TFEL panels require an AC voltage on the order of 100 to 200 volts. To develop panels, the accompanying driving electronics must also occupy a relatively small space. Most integrated circuits however, are designed to operate at voltages on the order of 10 volts. The production of integrated circuits to drive TFEL displays has received considerable attention as has work on the TFEL process to produce panels requiring lower voltages. Currently, integrated circuits to drive multiple rows of TFEL displays and with the capability for 16 levels of gray scale are being developed under ERADCOM support by Supertex and Hycom (Reference 3-17).

Electroluminescence can be produced by using ac or dc and thick or thin luminescing layers. Available commercial dot matrix displays are limited to the ac TFEL panels produced by Sharp. Currently, these are available in two formats (Reference 3-18), a graphics model (240 X 320 pixels) and an alphanumeric model (128 X 512 pixels). Figure 3.2-2 shows an example of the graphics panel. Smaller dot matrix displays, suitable for programmable legend switches are under development by other companies. Sigmatron-Nova has demonstrated small panels on the order of 2.5 X 2.5cm with resolutions up to 22 lines/cm (56 lines/inch). Lohja Corporation is also developing small dot matrix TFEL displays.

Color capability of TFEL devices has been limited to yellow to yellow-orange colors for devices on the market. The current displays use a zinc sulphide emitting layer doped with manganese. Different doping has been used to produce red, green, blue and white colors, however the display efficiency decreases radically and other colors on multi-color TFEL panels are still several years away.

3.2.4 Plasma Displays

Plasma displays have been established for a decade or more as a moderate size flat panel dot-matrix display. These displays use ac excitation of a neon gas layer between two glass planes with grids of X & Y electrodes. A basic advantage of the ac plasma display is its ability to retain an image once written without the need for continual refreshing. Ac plasma units are available in several sizes. A typical unit (Reference 3-19) offers an active display area 21 X 21cm (8.5" X 8.5") with resolution of 24 lines/cm (60 lines/inch). These units are configured as opaque or transparent. The transparent versions permit the projection of maps or other material on the back of the plasma panel allowing the panel to be used as a graphic overlay. The ac plasma has found limited use as a militarized display. Disadvantages of the ac plasma are the high driving voltage required (~200V) and a lack of gray scale control.

Most of the recent ac plasma display development has been in the area of alphanumeric character displays for terminals. Science Applications, Inc. is working on a very large (1 meter diagonal) plasma panel display for military applications. Small, dot matrix plasma displays suitable for switch legends are not presently available and have not been considered a strong contender for this application. While ac plasma panels have been made with a green color, the predominant color of commerical displays is neon orange.

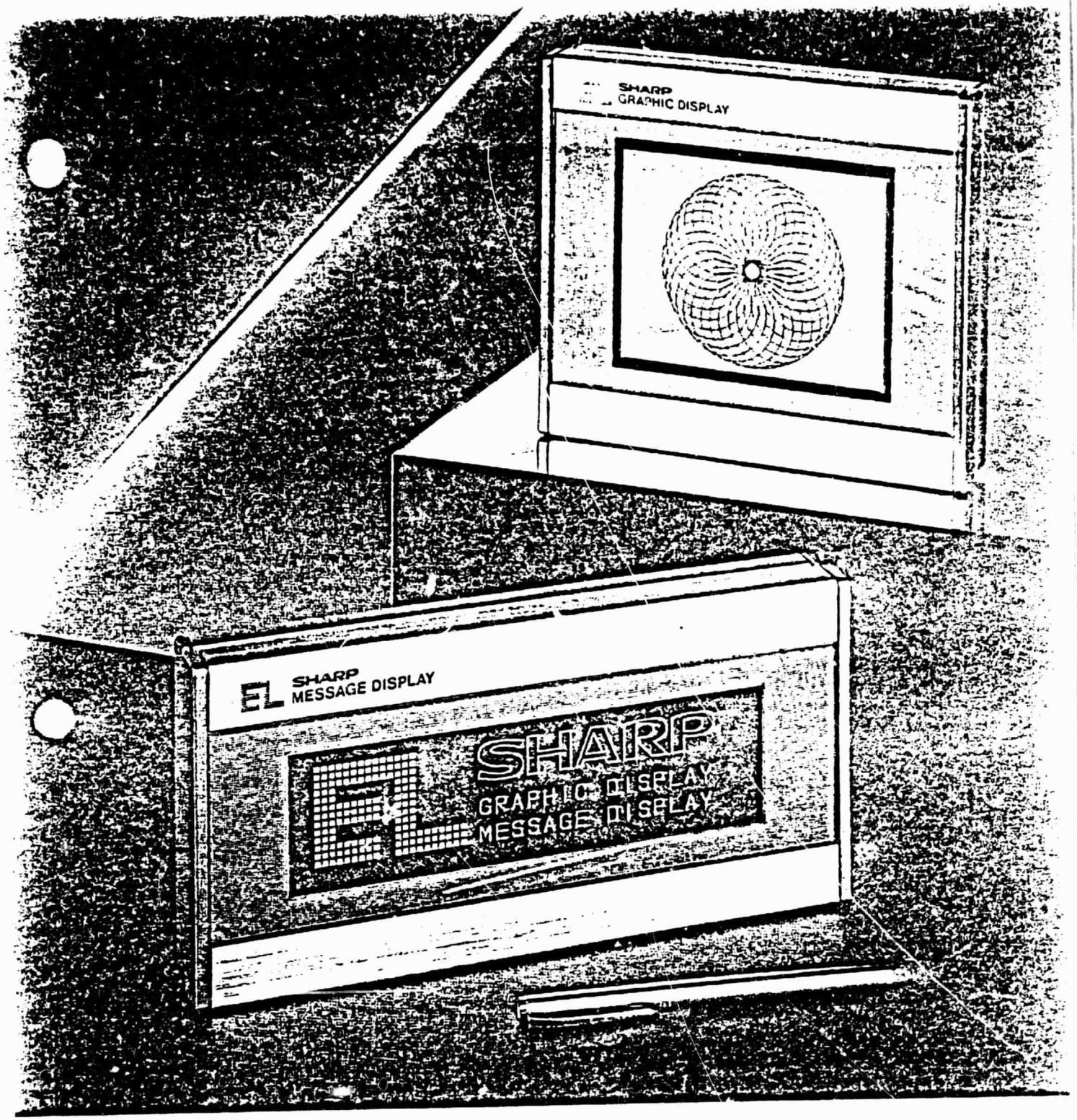

Figure 3.2-2: SHARP TFEL PANEL DISPLAYS

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Dc plasmas offer more color capability than ac plasmas and have been developed fairly extensively for use in terminals and other alphanumeric display applications. A limitation on the size of dc panels has been the need to refresh the display and avoid a flickering effect. This requirement has limited the number of characters per line to 40. The other primary development area of dc plasmas is large screen dc plasmas for use in flat screen television. Lucitron (Reference 3-20) is working on an 88cm (35 inch) diagonal screen which it plans to market soon. Manufacturers in Japan are also working on flat screen dc plasma displays. Once again, small, dot matrix dc plasma panels have not been seriously considered for switch legends on programmable legend switches.

3.2.5 Vacuum Fluorescent (VF) Displays

Vacuum fluorescent displays have found considerable application in calculators and other segmented character displays. Their construction is more complex than most of the other flat panel displays and they have only recently become available in dot matrix format (Reference 3-20). Most present dot matrix models are directed towards terminal, data display and word processing applications. Development efforts are also underway to combine vacuum fluorescence with integrated thin film transistors for use in flat screen video displays (Reference 3-22).

The lifetime of the VF displays are quite good (~50,000) hours if the displays are not used at high brightness levels. Required maximum voltages are lower (30-80V) than those needed for ac plasma or TFEL displays and quoted brightness levels are typically 100fL. The blue-green color matches the response characteristics of the eye better than the orange ac plasma displays. Small, fully populated dot matrices for switch legend use are not available however.

3.3 Display Comparison

The previous portions of Section 3 have described the displays presently available or under development for incorporation into MFDCS's. Figure 3.3-1 provides a summary chart of the various display types and some parameter ranges expected in the next few years.

Display	Luminous Efficiency (Lumens/Watt)	Resolution Range (lines/cm (lines/inch)	Color Capability	Gray Scale Levels	Dot Matrix Array Size (H X V)	Display Area H X V	Maximum Voltage Required	Lifetime (hours)
CRT Monochrome	10	26 - 43 (65 - 110)	Monochrome	256	2000 X 2000	75cm diagonal	12 - 16kV	2,000 - 10,000
(Beam Penetration)	4	26 - 43 (65 - 110)	Red - Green	256	2000 X 2000	48cm diagonal	10 - 20kV	2,000 - 10,000
(Shadow Mask)	3	32 (80)	Red - Green - Blue	256	1024 X 1280	75cm diagonal	10 - 25kV	> 1[illegible]
LED	0.1	13 - 51 (32 - 128)	Red - Green	8	256 X 320	10 X 12.5cm	10V	> 1[illegible]
LCD	Passive	12 - 20 (30- 50)	Black, Blue, Green, Yellow red (Single)	8	280 X 360	15 X 18cm	3 - 20V	> 5[illegible]
EL	1 - 8	28 (70)	Yellow - Orange (Single)	16	240 X 320	9 X 12cm	100 - 200V	> 50,000
Plasma	.3 - 3	12 - 24 (30 - 60)	Orange, Green (Single)	2	1024 X 1024	1m X 1m	100 - 200V	> 20,000
VF	4 - 8	20 (50)	Blue - Green (Single)	16	128 X 128	7.7 X 7.7cm	30 - 80V	> 30,000

Figure 3.3-1: DISPLAY PARAMETER COMPARISON

3.4 Human Factors

Multi-function displays present primarily alphanumeric symbols, special symbols and perhaps a few graphics primaries (lines, arcs, etc.), The numerous human factors parameters relevant to the display of these types of information have been summarized in several sources (References 3-23, 3-24, 3-25, 3-26). Only a few of the major parameters are covered here.

Numerous recommendations have been made for minimum symbol size. The required size differs with the manner of presentation, the characteristics of the symbol font and the particular application. Referring to the later category, for example, larger characters should be provided when correct discrimination is critical, when speed and ease of reading are improtant, and when each symbol is independent, as in a code number, rather than being partially redundant as in typical English text. Typical minimum symbol height recommendations are 15 to 25 arc minutes (Reference 3-24, 3-25). A frequently cited value for flight deck applications where a common viewing distance is 70cm (28 inches) is 5mm (0.2 inches). More critical data should of course be larger.

The issue of minimum contrast is also complicated by the existence of numerous recommendations and interaction with many other parameters. If the symbol contrast is too low, discrimination is difficult and time consuming. As the contrast increases, the symbol becomes more easily visible until a point is reached where the contrast is so high that the image "blooms" and becomes less visible. A minimum contrast ratio of 5 has been suggested for "at-a-glance" viewing under daylight conditions (Reference 3-25). The same source suggests an upper contrast ratio limit of about 80.

Measurement of the visual contrast of modern displays is complicated by the fact that some of these devices such as many LED's, emit light from several very small discrete areas. If these areas are smaller than about 0.7 to 1 arc minute, luminance measurements for determining effective display contrast should be made over an area about this large (Reference 3-25).

Color introduces another factor into the problem of contrast determination. If the color of a symbol and the background are markedly different this "color contrast" can add to the luminance contrast discussed in the previous two paragraphs to yield a

higher effective contrast. Methods for computing the contribution of color contrast have been proposed (References 3-27, 3-28).

The trend in modern electronic visual displays is to use dot matrix as opposed to stroke written or solid symbols. These dots may blur together slightly as on a typical raster CRT display or they may be physically distinct elements as on an LED, LCD or TFEL display. The minimum number of elements in a matrix used to generate a symbol has been the subject of several studies. A matrix of 5 by 7 dots is marginally adequate for numerals and uppercase letters (Reference 3-29) but a matrix of at least 7 by 11 dots (Reference 3-30) or 8 by 11 dots (Reference 3-25) is needed for ease of reading lower case letters. Even more dots are useful for rotatable characters, for minimizing degradation due to failed display elements and for complex special symbols.

3.5 Display Applications

Electronic displays are replacing electro-mechanical displays in many new aviation and ground based display and control system designs. The following examples illustrate some of the operational applications of the various different electronic display forms.

1. Cathode Ray Tubes - CRT's are now coming into common use in new aircraft display designs. Color shadow mask CRT's are used in the Boeing 757/767 aircraft. Monochrome CRT's have been used in AWACS consoles for some time in a controlled lighting situation. Flight deck uses of the monochrome CRT include the Orbiter installations and the F-18 cockpit.

2. Light Emitting Diodes - LED display applications in operational systems are still quite limited and relatively small in size. For example, the Boeing 747 employs an amber dot matrix LED chip made by Hewlett-Packard as a 16 character (2 rows of 8) display on an inertial navigation system control display unit. Segmented LED displays have found wide application in mobile radio equipment, timing equipment and calculators. Other, larger dot matrix LED displays are nearing operational status in the F-16 cockpit (see Section 7.3.2).

3. Liquid Crystal Displays - LCD's have been used primarily in low power applications such as watch, game and calculator displays. One current application of a small,

segmented dichroic LCD display is as backup engine status indicators on the Boeing 757/767 aircraft. Applications of more complex LCD formats in display and control systems are still in the development stage.

4. Electroluminescent Displays - EL displays are not currently used in operational display and control systems for airborne or ground-based vehicles. Operational application of these displays probably is still one to several years away.

5. Plasma Displays - Plasma displays have been available in militarized forms for several years. AC plasmas are currently in use in the military in several areas and programs. These include the control system for the seagoing cruise missile (Raytheon), an artillery fire control computer system (Norden), the Mulitple Launch Rocket System (MLRS) vehicle (Vought) and a portable landing and guidance system for remote airfield establishments.

6. Vacuum Fluorescent Displays - VF displays are currently used primarily in a segmented form for automotive dashboard applications. Dot matrix format VF displays have not been available for long and thus have not seen wide application.

4.0 DATA HANDLING AND PROCESSING

Much of the applicability of multifunction concepts to present and future display and control systems depends on the increased usage of digital processing for sensing, analyzing, displaying, and controlling parameters associated with the installation. the topics discussed below present some of the primary areas of concern in employing digital processing in multifunction display and control systems.

4.1 Processors

The processing power available to the designer of displays and controls has increased dramatically in the past decade. Inexpensive microprocessors have permitted the replacement of central computers providing a variety of functions by distributed processors performing specific functions and requiring only the appropriate data and a means of relaying results to the next stage of processing. These separate functions cover such areas as navigation, flight controls, communication control, crew alerting and warning, and display generation. Often, results from these computations are routed to a more general purpose computer for correlation, analysis, and command generation.

Processing speed has increased dramatically in recent years. New microprocessor designs can operate at 10 - 12 MHz clock rates and an increase to 15 - 16 MHz is projected for the next few years. This increase will probably represent a plateau until newer manufacturing techniques are developed (Reference 4-1). The standard eight-bit microprocessor has been joined by 16-bit microprocessors, with 32-bit models expected in the near future. In addition to the increased processing power, a much wider variety of microprocessors is available. This variety provides a wide range of I/O options, memory configurations, and compatability with specific electrical and environmental requirements.

4.2 Storage

Data storage requirements for systems applicable to the Orbiter vary from rapid access memory associated with program exectuion and display generation to longer term storage for programs, collected data, and data base information. The design of new materials and new record/playback capabilities has and will continue to greatly enhance the on-board data storage options and capacities.

4.2.1 Magnetic Tape

Magnetic tapes have been a standard means of storing data and/or programs in applications where immediate access is not necessary. A significant problem has often been the tape transport system which must execute a high number of start and stop operations. Another parameter is the amount of information which can be placed on a unit length of tape. Manufacturers are working to increase both the density and bit rate of their tape designs. For example, Ampex is developing a new tape form featuring a high bit rate (100 Mb/s)(Reference 4-2). At this point, the tape drives are fairly well developed and unfortunately, still present a major area of possible problems. Tape errors can be avoided to some extent by multiple recordings of the same data, and by fault detecting coding, but failure of the tape drive remains as a serious failure mode.

4.2.2 Disc Storage

Magnetic disks have been in use for some time as a storage device providing access time on the order of 0.01 to 0.1 second for large amounts of digital data. The availability of small disk systems has increased dramatically with the development of floppy disk and hard disk units for mini and microcomputer installations. At the same time the storage capacity of these disks has increased with improvements such as double sided, double density floppy disks. Disk technology is appearing in flight applications as well. The Boeing 757/767 aircraft store pertinent flight programs and data on a hard, fixed-head disk unit built by Sperry Flight Systems (Reference 4-3). This unit weighs approximately 2 kg, with a 15cm diameter and 8cm height. Storage capacity is 4Mbytes with 46 tracks and 46 fixed heads. Access time is approximately 5ms. Projected lifetimes is 10,000 hours.

Increased storage capacity is currently available using video disks. These disks store on the order of 30 minutes worth of prerecorded television images. This is the equivalent of 54,000 television frames, each with perhaps 3-4Mbits of information. Thus total storage capacity is on the order of $2x10^{11}$ bits. One form of video disk, the laser disk, is read by a small laser which is modulated by the recorded pattern on the disk. This reading technique has the advantage of requiring no head contact with the disk and hence no wear on the disk (Reference 4-4). The video disks mentioned are all prerecorded. A more useful video disk for the typical system would permit both reading and writing of information. Materials have been tested for use as a read-write video disk medium, but as yet the idea is still in the research stage.

4.2.3 Solid State Memory

The variety of solid state memory devices has progressed in much the same fashion and with much the same manufacturing techniques as have microprocessors. Physical size, access time, and cost have been continually reduced while the available storage capacity of individual "chips" has been increased. Currently, boards with 64kbytes of RAM are standard items. Chips with 64kbit capacity are on the market and Japanese firms expect to provide samples of 256kbit memory chips in the near future. Magnetic bubble memories offer another option for large storage capacity, although the development interest in these devices has slowed or been deleted recently in a number of companies. In general, given a similar manufacturing technology, solid state memory development advances should roughly overlap with those of microprocessor development.

4.2.4 Future Memory Options

Very large mass storage memories based on silver halide recordings are under development in at least two projects. Ampex is experimenting with this storage method (Reference 4-2) and the Harris Corporation in a project for NASA/Marshall Space Flight Center (Reference 4-5) has developed a microfiche storage and retrieval system capable of storing 10^{12} bits of information. Writing and reading are done on a silver halide film using He/Cd and He/Ne lasers, respectively.

4.3 Data Buses

Digital control and distributed processing require suitable data buses for data and command transmission between the various sensors, controls, and processors. Choices depend on the degree of redundancy required, the data rate, the number of transmitters and receivers to be served, and the protocol for determining transmissions by other transmitters on the bus. The 1553B bus operates with undetected bit error rates of 10^{-20} or better and word error rates of 10^{-6}. A 16-bit word is used for transmission.

Civilian aircraft employ the ARINC (Aeronautical Radio, Incorporated) data buses in various forms. These buses are simpler in that the data rate is lower (12-100 kb/s) and there is only one transmitter per bus. As a result, aircraft such as the Boeing 757/767 and earlier aircraft employ a large number of buses to carry the growing amount of digital data. The 767, for example, uses 120-130 buses. This results in a large amount of asynchronous I/O capability required on the flight management computer (FMC). This type of data bus will however, accommodate a wide variety of different transmitter speeds and data formats, thus allowing changes in equipment to be made without influencing the remaining buses.

A data bus currently being developed at Boeing for commercial aircraft also operates at a 1Mb/s rate, thus alleviating the slow speed problems of the ARINC buses. The new bus, designated DATAC (digital autonomous terminal access communication) is a serial data bus using a distributed control protocol. Each unit on the bus can transmit or receive, but cannot request data. Each unit is assigned to a time slot in a broadcast sequence. If a unit has no information to boradcast, the bus is structured so that each unit waits a unique predetermined time after which is has an opportunity to transmit. This bus is designed to be implemented in a voltage level, current loop or fiberoptic mode. A fiberoptic version has been installed on a NASA F-106 for use in thunderstorm research.

5.0 CONTROLS AND OPERATOR INTERACTIONS

The control techniques and interactions used in display and control systems vary considerably. In this section, some of the newer techniques applicable to multi-function display and control systems are discussed. While certainly applicable, the conventional components such as fixed function switches, joysticks, trackballs, lightpens, etc. will not be discussed here. Newer areas to be covered include touch panels, multi-function switches and voice interaction. The human factors aspects of these areas are also considered.

Light pens are not considered in depth here because they are not appropriate for shuttle flight deck applications. The chief advantage of a lightpen over a finger-touch panel is that the former can generally provide higher pointing and cursor positioning accuracy. This can be useful in graphics input but is not needed in the shuttle where the application involves menu selection and control activation. The major disadvantage of the light pen for this application is that the operator must grasp the light pen prior to using it to make a control selection and this will take more time than simply touching the control panel.

5.1 Hardware

An obvious choice for use in a multi-function system with programmable legends and a variety of displays is the CRT. Various techniques have been devised to use the versatile display capability of the CRT for multi-function purposes. These include selection of control action by moving a cursor, light pen indication and bezel editing switches. An outgrowth of these techniques is the current variety of CRT touch panel overlays available.

5.1.1 Touch Panels

Touch panels are used both in CRT screen applications and with other types of flat panel dipslays. In general, a touch panel is a transparent covering for a display in which the panel position touched by an operator is coded and passed on for appropriate reaction. Several types of sensing exist. These include:

1. X - Y grids of wires or conductors on separate transparent membrane planes. When pressed the X and Y coordinates of the point

touched are indicated. This type of touch panel typically has relatively coarse resolution.

2. Resistive layer and membrane. A conductive layer on a transparent membrane contacts a resistive layer on another membrane or CRT when touched. Alternate applications of voltage across the resistive layer in the X and Y directions defines an analog voltage at the point touched on the membrane. These voltages are converted to a digital format and recorded, thus indicating position to a typical resolution of one part in 256.

3. Capactive pickup. A series of transparent metallic pads are deposited on a glass plate. Leads from pads to the edge of the plate provide the connection to the remainder of the system. Touching a pad will change it's associated capacitance and thus indicate which pad was touched.

4. Acoustic echo. Acoustic waves generated by transducers at the perimeter of the display define an X-Y grid. Touching the panel produces an echo which is picked up by the transducers and processed to give a position. Typical operating acoustic frequency is 4MHz and spatial resolution is on the order of 1.2cm (0.5").

5. Infrared LED's. Infrared LED beams are detected by phototransistors accross the display. The LED-transistor network defines a X-Y grid of beams. When the display is touched, beams are broken and the X-Y position derived from centroids of the broken beam positions. This technique utilizes a differential mode to permit operation in a wide range of ambient light. Typical resolution is 0.62cm (0.25").

The first three techniques have the disadvantage of requiring an overlay on the display. This has a tendency to reduce visibility because of the coatings on the various membrane or glass layers. The second two techniques use sensing at the display perimeter and thus provide a clear display field. Techniques 1) and 3) result in a fixed format display. The other techniques permit redefinition of the display formatting

dimensions within the resolution of the touch panel. All of the techniques suffer from a lack of tactile feel or feedback when the panel is touched. A typically installation combining a display processor, CRT and touch panel is shown in Figure 5.1-1. This type of unit (Reference 5-1) is used during checkout of systems on the Boeing 767 aircraft.

5.1.2 Discrete Programmable Legend Switches

An alternative approach to combining switching and display functions is the programmable legend switch in which a small programmable display is provided with a pushbutton switch. This type of switch can then be located singly or in arrays to form a multi-function keyboard. An additional advantage is the ability of those switches to provide tactile feedback to the operator upon activation. Currently, the programmable legend switch is still in the development stage. A keyboard using small CRT tubes (2cm diameter) combined with switches has been designed, constructed and integrated into an advanced cockpit mockup at Boeing. This unit is currently being used as a multi-function keyboard (Reference 5-2).

As an alternative to the small CRT display, most efforts are now directed at using small flat panel displays as the display elements on the programmable legend switches. At this time LED arrays and LCD's are most often employed, although TFEL displays are looked at as a favored media several years hence.

Boeing, in conjunction with Micro Switch, Inc. is involved in the development of multi-function keyboards using LED arrays as the switch display (Reference 5-3). These switches will permit two rows of 6 5 X 7 dot matrix characters with a display resolution of 40 lines/inch. A drawing of such a switch is shown in Figure 5.1-2.

5.2 Human Factors

Touch panels tend to be more succeptible to accidental activation than discrete pushbutton switches. This occurs because most touch panels require little or no force or displacement and are relatively difficult to protect with guards between each switch. As a result of this susceptability, special care must be taken to avoid problems as a result of accidental control activation in a display/control system

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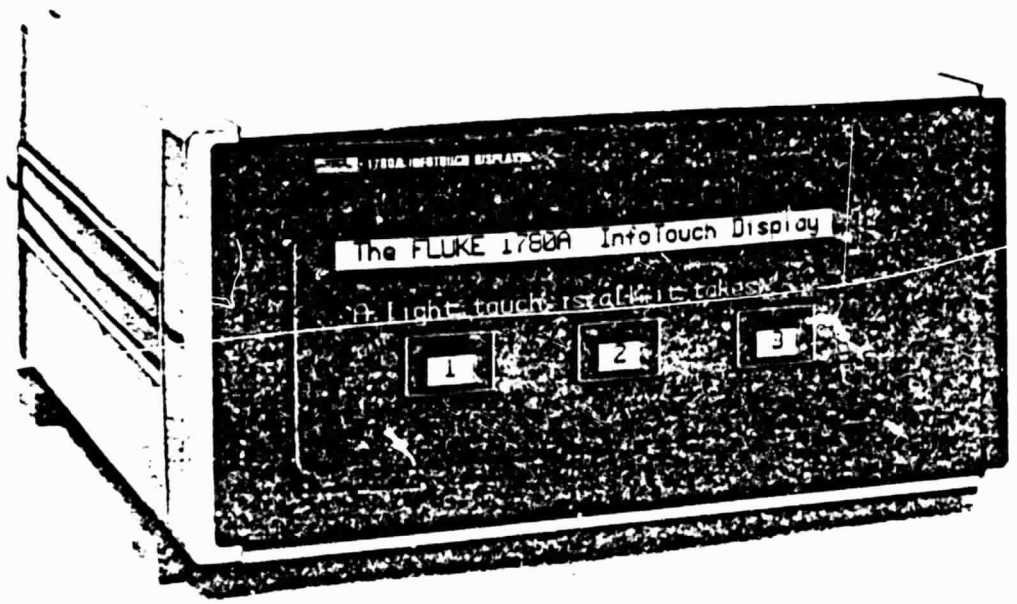

Figure 5.1-1: FLUKE INFOTOUCH DISPLAY

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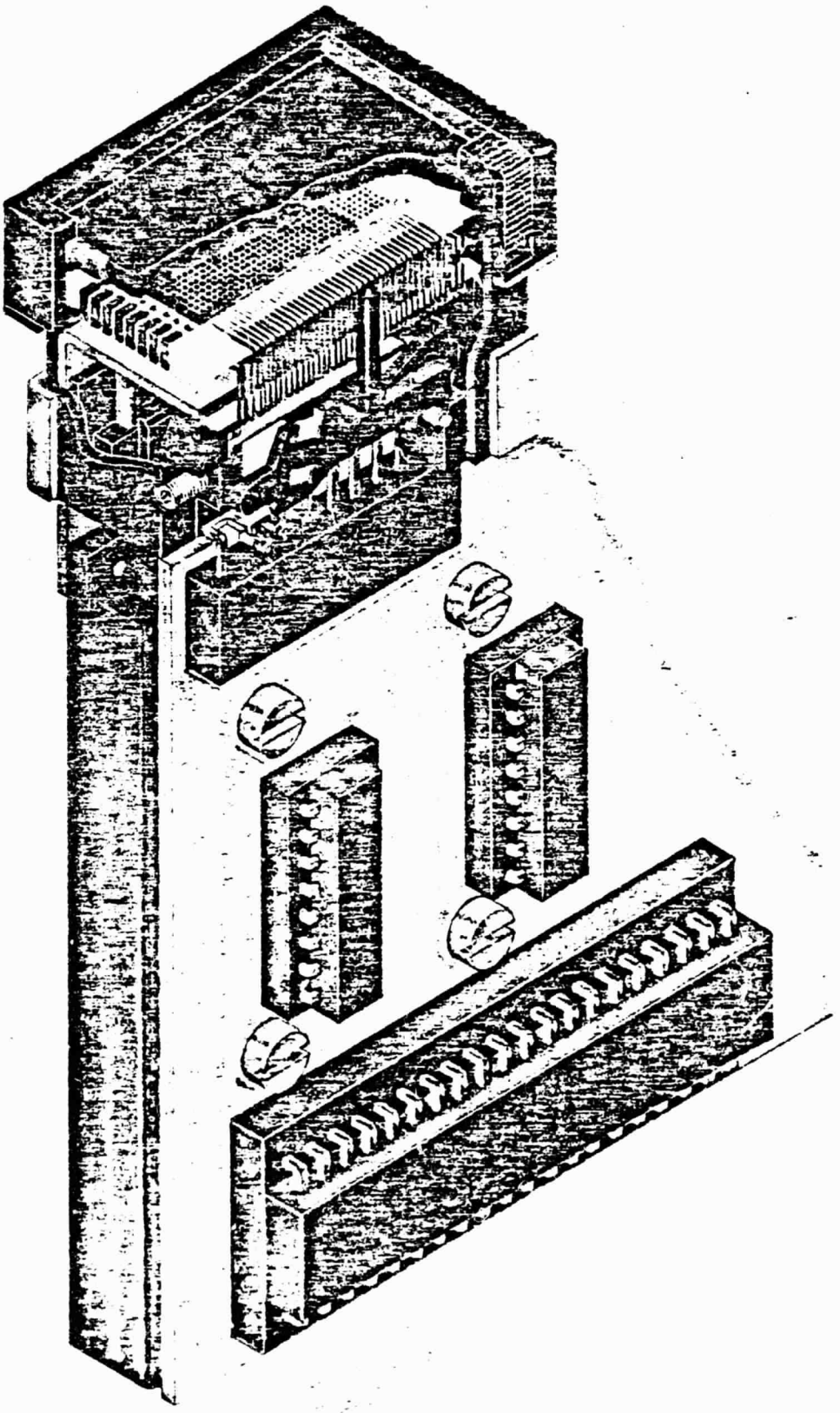

Figure 5.1-2: PROGRAMMABLE LEGEND SWITCH

incorporating a touch panel. In general, this is achieved by requiring critical control inputs to be followed by a second "enter" or "activate" input. Other useful mechanisms include control input validity testing to eliminate illogical and multiple inputs.

Feedback concerning control activation is essential in almost all human control use. The first level of feedback is an indication that the control has been activated. In a pushbutton this is ideally and traditional provided by tactile or "snap-action" feedback. Tactile feedback is not available in current touch panel designs. A usually acceptable substitute, assuming that the operator will be viewing a display while activating the control, is to provide visual feedback by momentarily dimming the display. This can be augmented by an auditory signal such as a click or a tone, preferably one under the control of the operator. The essential goal of this type of feedback is to remove any uncertainty on the part of the operator that control activation has occurred. In the absence of this type of feedback the operator may attempt to ensure an input by repeatedly activating the control, thereby generating multiple inputs, wasting time and increasing frustration.

The second level of feedback involves indication that the function intended to result from activation of the control has actually occurred. Whether and how to provide this level of feedback is not a control device consideration. However, as is noted in Section 6.0, it is essential to provide the operator with an effective indication of function status.

5.3 Voice Input Interaction

Voice input provides the operator with another control channel in addition to hands and feet. This can be very helpful if the operator's limbs are heavily loaded with control functions. There is an obvious potential for major benefits, for example, during low level flight in a single-place combat aircraft. If the operators limbs are not heavily loaded, the benefit available from voice input depends on the specific situation and on how adequately the voice input capability is integrated into the system. Backup of the voice input capability with regular hand-operated controls is generally essential. A MFDCS is well suited for this purpose.

Voice input systems require a mechanism to display the input command as it has been decoded, to provide prompts such as "please repeat" and to indicate the current operating mode of the voice input system. Voice synthesis can serve this purpose and may be very desirable if the operator should continue to look at some other display. Usually, however, a visual display is preferable. This reduces the load on the operator's auditory input channel, retains the message until the operator can attend to it and eliminates occasional complaints that voice feedback produces an undesirable echo effect. A simple auditory display such as a brief tone redundant with the visually displayed message "please repeat" can help increase operating speed.

Several voice input units are available on the market. A typical unit manufactured by Interstate Electronics has a 100 word recognition vocabulary and a claim of 99% accuracy. The operation of the unit requires a training procedure in which the words are repeated several times by the individual operator to "train" the voice entry unit. The unit, in effect, averages the repetitions to derive a typical frequency spectrum for that frequency and word. Short words and alphanumeric characters tend to be less accurate (~75%) than longer words. This type of unit is currently used in a Boeing computer aided drafting system with good results (Reference 5-4).

6.0 MFDCS DESIGN PRINCIPLES

The previous sections in this document covered the three major physical elements of a MFDCS the displays, controls and data processing. This section reviews some of the considerations in combining these three elements into a multi-function system. The emphasis here is on the operator interface with the MFDCS, and with the process by which an optimal MFDCS design will be achieved.

The essential feature that distinguishes a MFDCS from other display/control systems is that there are more functions than there are controls. Hence, some of the controls in a MFDCS must provide the operator with access to more than one function. This implies (1) a capability to associate several different labels with a single control, and (2) the necessity for the operator to perform several control actuations to access some functions.

Although there are many ways to configure a MFDCS, such systems have several common features. Because there are more functions than controls, there must be some orderly scheme for causing control labels to change and to thereby provide access to any required function. Usually this involves a hierarchy, or tree-like structure of successive "pages" or sets of functions. This "access schema" may be configured so that all functions are always accessible by stepping through a series of pages. Alternatively, only the subset of functions relevant to a particular mission phase may be accessible.

A primary consideration in MFDCS design is the specific system application. In every case, the design must be tailored to the specific functional requirements of the mission to be performed, the specific mission success criteria and the specific characteristics of the personnel who will operate the system. A mission consisting of several phases, where only a small subset of the total set of functions will be performed in any phase, can benefit if the function selection process is tailored to the mission phase. In this way, only the few functions actually needed will be available at any one time and access to any one of these will be relatively fast. If, however, the MFDCS is intended for use in a less structured mission environment it may be necessary for all functions to be simultaneously accessible. In this case the operator will, on the average, have to

step through a larger number of pages to access a particular function, thereby making each function harder to access. Similarly, the best MFDCS design for a situation where the most important criteria is operating speed will differ from the best design for a situation where the most important criterion is avoidance of operator errors. Finally, a system intended for occasional use by operators must provide more extensive prompting than if it is intended only for operators who will use it regularly.

A considerable amount has been written about features to incorporate or avoid in a MFDCS. Among this material is some useful research data. However, there are so many critical issues in a MFDCS design that only a very small portion have as yet been addressed through research. Many of the available MFDCS design principles are therefore by necessity based on subjective assessments by the designers or operators of existing systems, or on extrapolations from established human factors principles.

The material in the remainder of Section 6.0 derives from numerous sources. A particularly helpful general reference is the paper by Calhoun (Reference 6-1) summarizing design criteria. Interviews with personnel within Boeing and at Wright-Patterson Air Force Base who have been involved with the development or evaluation of MFDCS designs also were very helpful.

6.1 Potential Advantages and Disadvantages

The potential advantages and disadvantages of MFDCS's relative to dedicated displays and controls primarily involve panel space and volume, operator workload and the potential for operator confusion. Whether the result is positive or negative depends both on the particular application and the quality of the design.

A primary potential benefit offered by a MFDCS is a reduction in the number of displays and controls. This saves weight and volume. In addition, in a complex system it can improve operability by placing more functions in the operator's primary work area where they can be used more effectively.

A potential penalty imposed by a MFDCS is increased workload or reduced operating speed. This can result from the requirement to sequentially activate more than one control to access at least some of the functions in the system. Whether this penalty will occur depends on the particular application and on the sophistication of the designer. If the application requires only a small subset of the functions to be available at any one time, with considerable control activity within this subset each time it is called up, it may be possible to configure the system so that all the functions within a single subset are simultaneously available. In this case the major workload penalty will be the calling up of the subset of functions and this may be more than compensated by having all the displays and controls in the primary work area.

In other applications, the workload may be reduced by a MFDCS. Consider the situation where the tasks to be performed fall into a complex sequence that would have to be defined by a checklist in a system incorporating numerous dedicated displays and controls. In this case it may be possible to actually reduce operator workload by configuring the MFDCS to automatically make the needed display and control functions available at each point in the task sequence, and by providing prompting to remind the operator of what actions to take next.

In comparison to dedicated display/control systems, existing MFDCS's seem to be less obvious in their operation. This occurs particularly at key points such as when first activating the system or after making an error that leaves the operator in a software trap from which there is no apparent exit. Few things are so frustrating to an operator as being unable to elicit an effective response from a system. With dedicated controls, one can generally throw switches until something happens but a MFDCS may just set there, passively waiting for some action that is not at all obvious to the operator. While this trait is a disadvantage of numerous existing MFDCS's, it is not fair to classify it as a disadvantage of the MFDCS concept. Instead, through careful use of control labeling and display prompts, the designer can eliminate this type of problem. This topic is discussed more fully in Section 6.3.

6.2 Design Alternatives

There are many alternative approaches to the implementation of MFDCS. A few of these are summarized here for the purpose of making the MFDCS designer aware of the range of options that should be considered. The pros and cons of each approach are mentioned when appropriate but are primarily covered in the discussion of design principles in the next section (Section 6.3).

Alternative approaches reviewed here include:

1) Label placement on or to the side of each control.
2) Graphical versus tabular presentation.
3) Level of control.
4) Integration of checklists into the MFDCS.
5) Tailoring of control access options to mission phase.
6) Automatic reconfiguration to achieve requested action even after component failure.

Label placement. Associated with each control in most systems is a label identifying the function associated with that control. There are two approaches to control label placement in a MFDCS. The label can be on the front surface of the control, as in the UDACS unit illustrated in Figure 7.2-1 in Section 7.2 and in the discrete programmable switch illustrated in Figure 5.1-2 in Section 5.1. Alternatively, the label can be displaced to the side of the control as in common display/control units consisting of a CRT with a column of bezel-mounted pushbuttons along each side. The bezel switch approach is illustrated by the 757/767 Flight Management System Control/Display Unit illustrated in Figure 7.1-2 in Section 7.1. This issue of label placement is more important in a MFDCS than with dedicated controls because with the former approach the user remains more dependent on reading the label to determine what function is currently accessed by the control.

Labeling on the control itself is preferable because it makes it more immediately obvious to the user which label is associated with each control. This is particularly true if the alternative is a CRT with pushbuttons on each side that are in a different plane than the CRT display face. In this situation parallax between label and control whenever the user is off-axis from the CRT can cause serious confusion about which control is associated with each label.

A potential advantage of the CRT plus pushbuttons approach in some situations is that it is (usually) possible to use longer labels on the CRT than on the labels incorporated directly in a switch. This is more likely to be advantagous in a system used by relatively inexperienced personnel who may need complete labels to understand how to operate the system. Experienced users, in contrast, will be familiar with the numerous acronyms and abbreviations that define the components and functions of the system and should have no trouble with briefer labels.

Graphical Presentation

In some situations, graphical display of the status of controlled functions can be much more effective and easier to interpret than a simple tabular display (for example, see Reference 6-2). The graphical approach can be particularly useful in illustrating the status of valves, switches and even flows and pressures in a complex plumbing or power distribution system. Ideally in such a situation the user can change the setting of a valve or switch simply by touching the symbol representing that device and then receive immediate feedback indicating how the operating mode of the controlled system will be affected. Graphical presentation can also be useful in illustrating variables that have some spatial reference, such as quantity of stores at various storage sites.

Graphical presentation imposes additional demands on the display/control system. If the controlled system is complex, graphical presentation is likely to require higher display resolution and more sophisticated data processing than tabular presentation. In addition, for full effectiveness, graphical presentation requires some type of touch panel, light pen or very easy to use cursor rather than just the simple pushbuttons that suffice for a tabular presentation.

Level of Control

One way for an operator to control a complex system containing many discrete elements (relays, valves, etc.) is to individually set each element to achieve the desired system configuration and operating mode. A higher control level results if the operator can instead select from among several predefined operating modes, after which the computer actuates the individual system elements to arrive at the required system configuration. With this approach, the operator preparing for an Orbiter OMS burn might choose between modes such as

"consume fuel from A tanks", "consume fuel from B tanks", or "consume fuel to optimize center of gravity for re-entry". The computer would then automatically actuate the proper valves and relays. This type of high level control is particularly well suited to MFDCS.

Potential advantages of a higher level of control include reduced operator workload and reduced chance of operator error during critical mission phases. These can result because the operator has fewer controls to actuate and fewer choices to make. The available choices are expressed in terms more directly related to immediate mission goals, thereby reducing the need for the operator to recall the details of how the system functions.

The use of high level control imposes an additional load on the system design process. The entire set of system operating modes must be identified so that they can be incorporated into the system software. Hence, the system functions and function flow at each point in the mission must be well understood.

For some systems it may be necessary to provide an additional, backup control mode where each individual system element is directly controllable by the operator. Using this backup mode, any system configuration available with discrete switches would be available. In this mode, the hierarchical access scheme of a MFDCS would require more operator actions and hence might be slower than a discrete control system. However, the amount of prompting and computer analysis of control inputs available with the MFDCS might make it easier to operate than the discrete controls.

Integration of Checklists and Procedures

For many systems, procedures are so complex that extensive checklists are required to aid in recalling the proper operating sequence. These checklists can be largely eliminated by the prompts and automatic sequencing from one set of control options to the next that are incorporated into a MFDCS.

Tailoring of Access Schema to Mission Phase

The access schema for a particular MFDCS can be fixed or it can vary as a result of some condition such as mission phase. If distinctly different subsets of system functions are used in different mission phases, it is generally preferable to

reconfigure the MFDCS access schema for each mission phase. In situations where this reduces the number of operator control actions required to access the frequently used functions, it can reduce operating time over a fixed access schema (Reference 6-3).

Automatic Reconfiguration

Because a MFDCS is computer based it is ideally suited to automatically reconfigure the system under control and thereby achieve the commanded result even though a portion of the system has failed. This might involve, for example, automatically switching the electrical power distribution system to another fuel cell if one cell in use fails during a critical activity.

Given the limitations on Orbiter resources, automatic reconfiguration is not desirable in every situation. Instead, it will be necessary to develop a set of groundrules reflecting the relative importance of completing various activities and conserving certain resources. If fuel from one tank becomes unavailable, it might for example, be appropriate to switch to a different fuel tank during an OMS deorbit burn but not during a routine orbit adjustment.

6.3 Design Principles

Many of the human factors design principles that apply to a MFDCS are the same as apply to any system consisting only of dedicated displays and controls. For example, the system must be as simple as possible to learn and to operate. To minimize workstation clutter and overcrowding, the functions available to the operator must be limited to those that are truly essential. The most critical and most frequently used functions should be closest to the operator's primary work area.

The unique aspects of a MFDCS require the application of, or at least more emphasis on, additional human factors design principles beyond those that apply to dedicated controls and displays. Some of the major principles identified at this point in the evolution of the MFDCS are summarized here. These derive from many sources including Boeing design experience. A primary reference is the 1978 review paper by Calhoun (Reference 6-1).

Provide maximum operating flexibility

The MFDCS should not constrain the operator to perform control actions in any particular sequence solely for the convenience of the designer.

Make the most critical or most used functions the most accessible

Control functions that are the most time critical or that are used the most should be the most accessible to the operator. In most cases this means they should appear highest in the access hierarchy. In some cases it means that they should be available on dedicated switches rather than within the multi-function hierarchy.

Minimize number of operator actions

The time taken by an operator to access a particular function increases with the number of operator actions required (Reference 6-3). Hence the MFDCS function access schema should group functions that are used together on the same or adjacent pages. Also, it should place the most frequently used functions near the top of the access schema. Functions used with extreme frequency, or which must be accessed with extreme speed because of their importance, may even deserve to be implemented in dedicated swithces.

Minimize number of indenture levels in the access schema

One way to minimize the number of operator actions required to access a particular function is to minimize the number of indenture levels or steps in the access schema. Maximums of two to four switch actions following the first page of functions have been suggested. This number should be minimized but the precise limit is mission and system specific and depends on the number and time criticality of the functions to be accessed and the number of control devices that can be accommodated at the workstation.

Tailor system to current operational situation.

In many applications, certain functions are used frequently in some mission phases or situations, but are not used in others. The access schema for a MFDCS used in this type of application should be tailored to each mission phase, thereby reducing the number of operator actions required to access the most used functions. (NOTE: The advantages of tailoring the access schema to each mission phase must be weighed against possible increases in operating difficulty

that can result from the user being required to learn several different access schema.)

Assign functions to particular multi-function switches for most efficient access.
Several factors contribute to the accessibility of an individual function within a page of the access schema. First, functions within a single page of this access schema should be grouped logically. This usually means either that similar functions should be grouped together on the page, or that the positioning should correspond to the normal sequence of operations. Second, related functions that appear on different pages should be in a consistent location, thereby making these functions easier to locate within each page. Third, the most frequently used functions should be in the most easily accessed locations. In most situations these will be the corners of the control array.

Provide for rapid movement through pages of the access schema
Time spent in moving from one page to another in a MFDCS access schema decreases operating speed below that possible with dedicated switches. Hence it should be possible to move rapidly from one page of the access schema to another. If pages are arranged in a linear sequence, so that the operator does not have to choose from among several branches, a three-position center-off toggle switch may be the most convenient device. It allows movement to the next page in either direction using a single device. In other situations, it may be possible to configure the access schema so that selection of one function automatically cycles the system to the page containing the next set of functions involved in the task sequence.

Provide automatic reverse through the access schema when this is useful.
Automatic return to a previous page of the access schema after an interval of perhaps 10 seconds with no new input by the operator can reduce operating time (Reference 6-4). This approach is only appropriate in situations where such an interval of no activity consistently implies that the operator is finished with that page and where the operator consistently needs to return to a higher level in the access schema, rather than progressing to some other page involved in a task sequence.

Provide easy access to current function status (on/off, etc.)

In most situations the operator requires at least occasional access to information about the status of particular functions, such as which radio channel is selected or whether a particular valve is open or closed. Dedicated switches usually provide a direct, immediate display of this information. A MFDCS generally does not indicate function status unless the designer makes special provisions for incorporating this information into the display. If not permanently displayed, this information should be very easily available to the operator.

Provide maximum prompting that does not interfere with system operation.

One of the major potential advantages of a MFDCS over dedicated switches is the capability for providing the user with help in recalling how to operate the system. It is especially important for the MFDCS designer to provide this type of help because the operation of a typical MFDCS is much less self-explanatory than for a typical dedicated control system. Messages on the display or intensification or blinking of certain switch labels can be used to indicate what control options are available to the operator at that moment. If the system is ever used by individuals who are not intimately familiar with how it operates, particularly helpful prompts may include indication of which control actions start or initialize the system, cancel an input, turn off or deactivae a particular function or move backwards through the access shcema to arrive at an earlier page of functions. A difficulty with such prompts is the fact that they consume a portion of the display capacity and they add clutter that reduces the interpretability of the display. An operator who is highly experienced with the system will not need most of these and will find them an interference. These individuals should be provided with a means of suppressing or at least reducing the prompts.

Identify active switches

In a typical MFDCS, only a portion of the controlled functions displayed are active at any one time. For example, after starting to make a numeric entry the only probable valid inputs are another numeral, an "enter" command, a "cancel input" command and perhaps a "backspace" command. As an extension of the prompting described in the previous paragraph, the operator should be made aware that these are the only valid control inputs. This might be achieved by

intensifying the labels on these controls, or by some other coding dimension such as color.

Provide a preview mode for critical operations

Controls that have a major impact on the system will occasionally be activated in error. Hence these functions should not be implemented immediately upon activation of the control. Instead, they should require confirmation by operator depression of an "enter" or "activate" control. It is essential to provide a prompt such as blinking to remind the operator of the need to actuate this latter control.

Provide a preview mode for complex operations

In a complex system containing many controlled elements such as valves and relays, or a complex process involving many operator selections, the operator requires some means of previewing the selected configuration prior to activation. Graphical presentation can be particularly beneficial since it can illustrate both the selected configuration and the mode of operation. For a fuel or electrical power distribution system, this might involve the illustration of pressures or flows. For a maneuver it might involve graphical portrayal of vehicle attitude, velocity or position throughout or after the maneuver.

Allow easy correction of operator inputs

A few operating errors are inevitable. In addition, the operator will sometimes change his or her mind after activating a control. In either case, easy cancellation of a control input is essential. Several cancellation mechanisms can be helpful. For example, a single activation of a "cancel" or "clear" control might erase the last digit of a multidigit entry and a second depression might erase the entire entry. A "page cancel" or "menu cancel" control might cause the MFDCS to move in reverse to a previous page in the access schema each time it is depressed.

Validate operator inputs as they occur

At any point in time the MFDCS operator will be able to make some control inputs that are not valid, either because they are not logically consistent with other inputs or the current operating mode of the system, or because they are outside of set limits. Examples might be selection of a communication channel that does not exist, or input of a numeral when a letter is expected. The

operator should be informed about these errors immediately after they occur. If possible, a message that will aid the operator to understand the error and to select a correct response should also be provided. A desirable second level of validity checking involves selections that are logically correct but which can lead to a marginal or improbable condition. Examples might be a low fuel level or an orbit outside of the range anticipated for the mission. Failure to pass this test might simply activate a caution message rather than a warning signal.

Rely on recognition memory instead of recall memory

Individuals are to recognize many more commands and system functions than they can recall. This is well illustrated by the fact that individuals recognize many times more words when reading than they can recall for use when speaking. This principle can be applied advantageously in a MFDCS by always providing the operator with a list of available control options, rather than forcing the operator to recall a desired option from his or her memory.

Ensure that each control and label are unambigously associated

A common implementation of a MFDCS involves a display, usually a CRT, with a column of pushbutton controls on each side. This can result in a significant separation of controls from their corresponding labels. If the front surfaces of the controls are not close to and in the same plane as the display surface, parallax can seriously interfere with the ability of the operator to rapidly and accurately associate a label with the corresponding control. This problem will be aggravated by off-axis viewing.

6.4 MFDCS Design

Regardless of wheather a display/control system is multi-function or involves only dedicated displays and controls, there are many similarities in how it is designed and evaluated. The design process for either type of system begins with a definition of the functions the system must perform and proceeds through successively more complete stages from conceptual to preliminary to final design. An essential part of this interactive design process is the evaluation of the design as it exists at each stage. In both situations the evaluation is against similar criteria such as minimum operator workload, minimum chance of operator error, minimum operating time and minimum training requirements.

The design process can be largely informal, as is described in Section 6.4.1. Alternatively, it can be performed with relative formality using a design procedure such as that described in Section 6.4.2. Whichever level of formality is used, each of the steps described in Section 6.4.1 must be performed, although not necessarily in the exact sequence listed there.

6.4.1 Design Process

The basic features of an informal procedure for developing a MFDCS are summarized in this section. The following steps are required:

1. Define system functional requirements.
2. Establish characteristics of access schema.
3. Establish characteristics of display/control hardware.
4. Develop detailed design specification (access schema, control labels, etc.).
5. Evaluate result and interate (Steps 2 - 4) as necessary.

Step 1 - Define functional requirements.

The functions a system is to perform must be defined before any useful design activity can occur. (Reference 6-5 provides a useful summary of methodology for defining the functions a system is to perform.) This definition of system functional requirements is the most critical step in the design process. Errors here will compromise system success and usually cannot be compensated for in subsequent design steps. Errors involve either missing functions or inclusion of unnecessary functions. Failure to include an essential function is the more obvious error and hence is usually the object of greatest concern during the design process. Experience in the design of display/control systems suggests however, that the more common problem is the tendency to include too many functions that are not really needed by the operator. When these are included in the system they add clutter that makes essential functions less accessible. Hence, each proposed function must be evaluated to determine if it really must be accessible to the operator. It may be better instead to either fix the function to a single value, control it automatically, make it accessible only during maintenance (which might be performed by the operator using special maintenance instructions and access codes) or perhaps even exclude it from the system.

Once the essential functions have been identified, each must be evaluated in terms of how accessible it must be to the operator. This involves factors such as how rapidly and how frequently it must be accessed. For example, a control to change radio channels might need to be easily accessible because it will be used very frequently and a fire extinquisher control might need to be easily accessible because of its criticality.

At the end of this step, the following information must be available to the MFDCS designer:

- A description of the functions that must be accessible to the MFDCS operator.
- The access priority of each function based on factors such as criticality and frequency of use.
- The relationships among the functions in terms such as which precede or follow which and which may be performed at various points in the mission.
- The information that must be displayed to the operator in support of each function.

Step 2 - Establish characteristics of the access schema.

At this point in the design process the groundrules for the access schema are established. What are the maximum number of indenture levels to be allowed for accessing functions of particular priority? Will movement from one page to the next be automatic or only at the specific request of the user? Will functions be grouped on the basis of similarity or by sequence of use? Will the access schema be fixed or will it be tailored to mission phase? What is the maximum number of functions that must be simultaneously accessible?

Step 3 - Establish hardware characteristics.

The simplest and hence the most common approach is to establish the general characteristics of the display and control hardware prior to performing the detailed system design. For example, will the hardware consist of a matrix of discrete programmable pushbuttons, a CRT or flat panel display overlaid by a touch panel, or a CRT or flat panel display surrounded by pushbuttons? How many switches will be available and how many characters can be used to label each? How many dedicated switches will be included? Will there be separate scratchpad and message display areas and how many characters will they contain?

In theory, it might be desirable to delay definition of the hardware to later in the design process when the access schema has been well defined. In practice, it is easier to perform the detailed design using a specific set of hardware. In any case, the hardware can usually be changed if it appears to be imposing a penalty on the system as the detailed design evolves.

In most cases the suitable hardware choices are limited by numerous factors. It must be available within the system delivery time and cost constraints. ' must function within the anticipated physical environment and must achieve the required reliability. It must fit in the available panel space and depth.

Step 4 - Develop detail design specification.

As the title of this step implies, it yields a detailed description of each function and how it fits into the MFDCS. The step starts with the assignment of functions to pages based on criteria such as similarity or the need to be simultaneously accessible to the operator. Next these pages are assembled into the hierarchy that makes up the system access schema. During this process of assigning functions to pages and organizing the pages, the maximum indenture level for each function is fixed by the priority of that function as established in Step 1. The highest priority functions may even be assigned to dedicated controls at this point.

Next the interconnections among the pages are established. These involve a definition of which pages follow or are accessible from each page and a description of how this transfer is to be initiated. The transfer might be at the specific request of the user.

At some point in this design process it is necessary to decide whether or not each function should occur immediately upon switch depression. Functions that have a major impact, such as opening a fuel valve, may require confirmation of operator intent by activating of a second control labeled "enter" or perhaps "activate".

Next, the labels, prompts and messages to be displayed to the operator are defined. These must clearly identify each function and the result of depressing

each control. They should also make clear to the operator the current status and operating mode of the system and what control options are available at that moment. They must also include or provide instructions describing how to access any data essential to the operator such as fuel quantities.

The output of Step 4 includes a detailed specification describing each function, how it is accessed and what actions it causes, as well as the controls, labels and messages involved in the system. This specification provides the basis for the subsequent design of the hardware and software that will make up the system.

Step 5 - Evaluate design.

The last step involved in developing a detail design specification for a MFDCS is evaluation to determine if the design is acceptable. Steps 2 to 4 will be repeated and the resulting design evaluated several times as the design becomes more and more firm; the evaluation in each case will be correspondingly more complete, realistic, and expensive.

While the design is still in the conceptual stage, it must be reviewed to ensure that all of the essential functions are implemented and are available to the operator when required. This is a largely analytical process of comparing system functional requirements with display/control system capabilities, function by function within the context of typical mission scenarios.

As the system definition progresses to the preliminary design stage, it becomes appropriate to evaluate the design in terms of operator workload using some method such as the Subsystem Workload Assessment Tool (SWAT) (Reference 6-6). This is a computer program that sums theoretical movement and dwell times for the operator's hands and eyes while using the MFDCS to perform the functions required by a specified mission scenario. Cognitive workload is not included in SWAT and must be evaluated qualitatively at this stage. Although it is limited in scope, SWAT is simple to apply and produces easily interpreted results that have value in comparing different designs.

As the system definition reaches the final design stage, a more complete and time-consuming workload assessment is desirable. This serves to identify points in the mission where the operator may be overloaded. If such situations are

found design revisions should be considered. An appropriate technique for this assessment is Timeline Analysis (TLA) (Reference 6-7). In this computer program the time available to perform each function within the mission scenario is divided by the time required by the operator to perform this function using the MFDCS. The time available is derived from the mission scenario. The time required is derived from programs such as SWAT and from the results of stopwatch measurements made using simulations of portions of the MFDCS. Obviously the validity of both sets of time estimates affects the validity of this approach.

When the design becomes sufficiently firm to justify the cost, the evaluation advances to the level of simulator testing. While this gives considerably better information about the adequacy of the display/control system than the previous evaluation techniques, the validity of the results still depends on numerous factors, particularly the realism of the mission scenario and the completeness of the operator training.

6.4.2 Formal Design Procedure

A more detailed and formal procedure for the design of a MFDCS was developed by Graham (Reference 6-8) and is summarized here. For additional detail Graham's report should be consulted.

As Figure 6-1 illustrates, this procedure involves twelve defined steps plus several decisions and branching blocks. The actions involved are as follows:

Step 1 - Establish the scope and constraints of the multi-function display/control system (MFDCS) design.

Define or ascertain the extent and limits of the MFDCS application within whatever larger context, if any, it will operate. Determine which systems or which portions of systems will be analyzed, in later steps, for identification of control functions. Ascertain whether or not any systems or equipment within the MFDCS scope have growth potential, i.e., may be enlarged or expanded in the forseeable future. Find out what constraints, if any, will be imposed on the design. Constraints probably will not affect the design until the configuration step (Step 10), but the designer should be aware of them at this point.

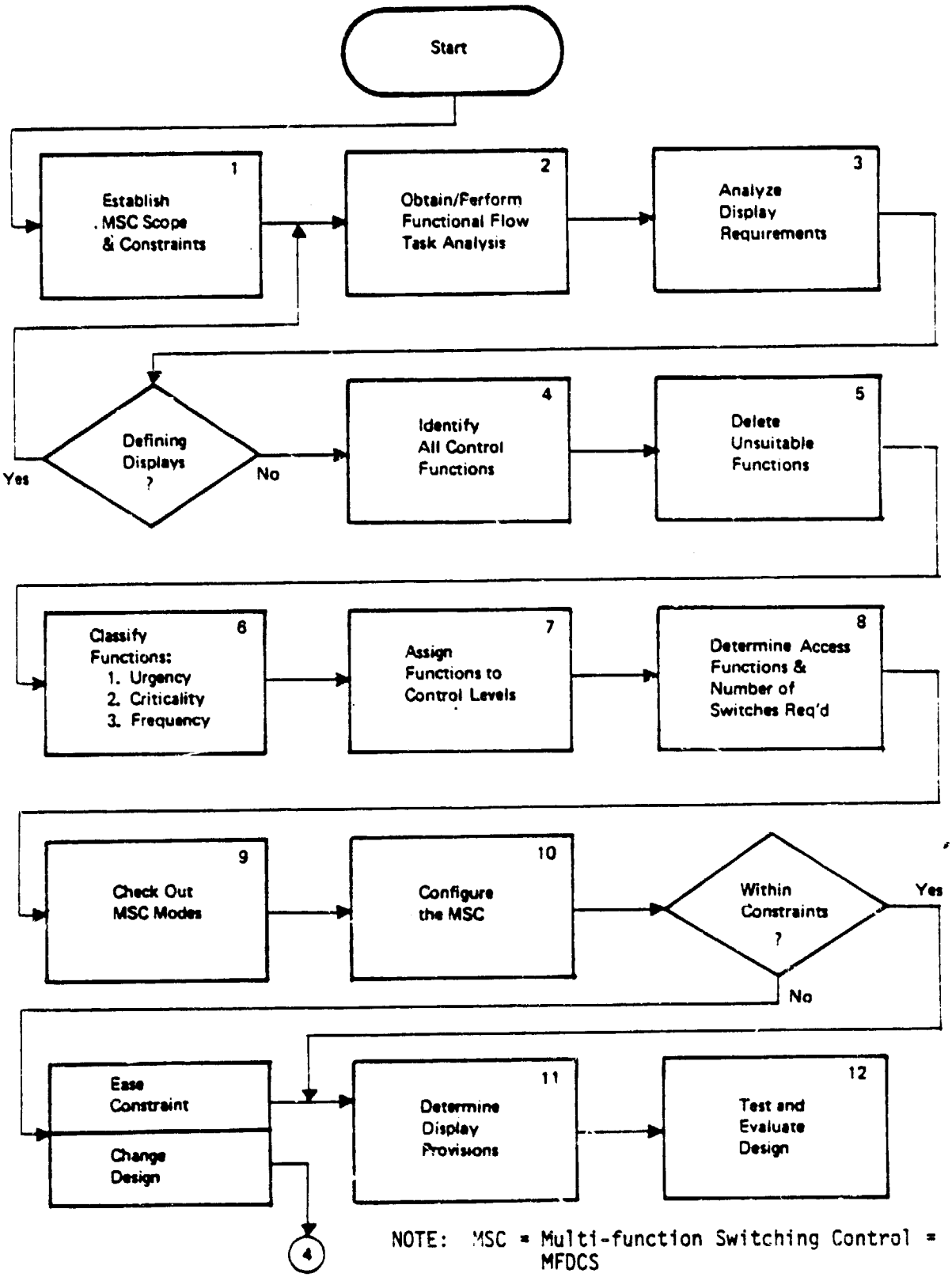

Figure 5-1: Block Diagram Summary of MSC Design Procedure

Step 2 - Establish a functional flow of operator tasks throughout the range of anticipated operations.

Find out what the operator wants to do, when he wants to do it, and why he wants to do it. Obtain or develop a time-based list of operator activity for all applicable missions and mission segments. Detail the control actions required of the operator and the information elements required by the operator within the MFDCS scope. Include emergency operations, degraded mode operations, and operations which may be added in the future if they are known or can be forseen. Construct a list of information required by and actions to be taken by the MFDCS user.

Step 3 - Analyze display requirements.

The primary purpose of this step is to identify switching requirements associated with displays within the MFDCS scope. A secondary purpose is to define the functions, modes, and information content of displays within the scope of the MFDCS.

If the MFDCS is to serve as the mode-control for existing displays, display-switching requirements should appear as "action requirements" in Step 2, and Step 3 is not applicable. In such a case, proceed directly to Step 4.

In all other cases, such as if displays are not yet defined or if the MFDCS is to be a subsystem mode control, proceed with the following subsets:

3A - Identify and list all information elements.

Most of these should already be listed in Step 2. Be sure to include all information elements relative to the "State" of MFDCS controlled equipment.

3B - Establish priorities of information elements.

Assign each element a priority for each mission phase based on criticality.

3C - Assign information elements to display elements.

Using the highest priority for each element, in any mission phase, assign each to a level in the display hierarchy. List the control functions (display-switching requirements) which result from these assignments.

If the purpose to this point has been to define a display sub-system, return to Step 2 of the procedure. Add display-switching requirements to the "action requirements" in the list developed at Step 2 then proceed with Step 4.

Step 4 - Identify all control functions within the MFDCS scope.

Complete the list of control functions, using the list from Step 2. List all control functions, regardless of type.

Step 5 - Identify MFDCS - Incompatible functions.

Delete control functions which are not suitable for the MFDCS. Assign deleted functions to more appropriate controls.

Step 6 - Classify control functions.

List MFDCS functions. Classify each function in each mission phase with a 3-digit code representing the function's (1) urgency, (2) criticality, and (3) frequency of use.

Step 7 - Assign functions to control levels.

Using each function's highest classification, assign each function to a level of control availability. If necessary or advisable, designate more than one primary MFDCS mode.

Step 8 - Determine access functions and number of switches required.

Designate access functions for secondary and tertiary mode groups. Include access functions and their necessary levels on the function list. Determine number of switches required for the MFDCS according to numbers of functions in various levels.

Step 9 - Check out MFDCS modes.

Tabulate functions and modes. Indicate mode change for each function operation. Check that (1) all secondary modes may be reached from the primary mode, (2) "return to primary" may be accomplished from all modes, and (3) mode "lock-up" never occurs.

Step 10 - Configure the MFDCS.

Ascertain hardware to be used, constraints, specifications, and eventual location of the MFDCS. Resolve conflicts, if any, of constraints vs. design evolved. Lay out candidate configurations. Assign functions to switches for all modes. Manipulate switch assignments and configurations, taking maximum advantage of the logic interface capability. Strive for (1) maximum function availability, and (2) minimum pilot workload.

Step 11 - Determine display provisions.

The display potential of the MFDCS is now known. Refer to Step 3C and assign information elements to either an MFDCS mode or an auxiliary display, as appropriate.

Step 12 - Test and evaluate the MFDCS.

Perform desktop tests, mockup tests, simulator tests, and flight tests. Plan tests carefully and obtain quantitative test data. Reflect design changes in proceeding paperwork.

7.0 MULTI-FUNCTION SYSTEMS

The development of multi-function systems is an expanding field with relatively recent beginnings. As a result few systems are operational and most of those that are do not represent completely multi-function display and/or control systems. Several of those systems investigated for this report are described below.

7.1 Boeing 757/767 Display and Control System

The display and control system developed for the new Boeing model 757/767 aircraft incorporates a number of features involved in completely multi-function systems. The heart of the Flight Management System (FMS) is the Flight Management Computer (FMC) which receives information from other onboard computers, from stored data and from aircraft sensors. The Control Display Unit (CDU) is the primary communication mode between crew and FMC. Figure 7.1-1 shows a functional overview of the system, while Figure 7.1-2 shows the CDU layout in detail. This figure is taken from a Boeing document (Reference 7-1) which describes a variety of flight management and navigation systems as well as considerations in a multi-function system design.

The 757/767 FMS incorporates considerable processing in distributed processors associated with inputs to the FMC. These processors communicate via a series of Aeronautical Radio Incorporated (ARINC) buses with only one transmitter per bus. The number of receivers per bus is not limited to one. The bus is relatively slow in comparison with buses such as the 1553 (100KHz at its highest speed according to Reference 4-6) but performs satisfactorily.

The FMC incorporates RAM memory (64K), EPROM memory (98K) and a 250Kbyte hard disk with fixed heads. This memory complement stores the operating program, flight performance data base and a navigation data base. Data is also recorded in flight for later use in analysis or maintenance.

The CDU incorporates a keyboard, scratchpad and bezel switch array, keyboard selectable modes of operation to be displayed and capability for pilot data selection and entry. The top row of switches on the keyboard defines various

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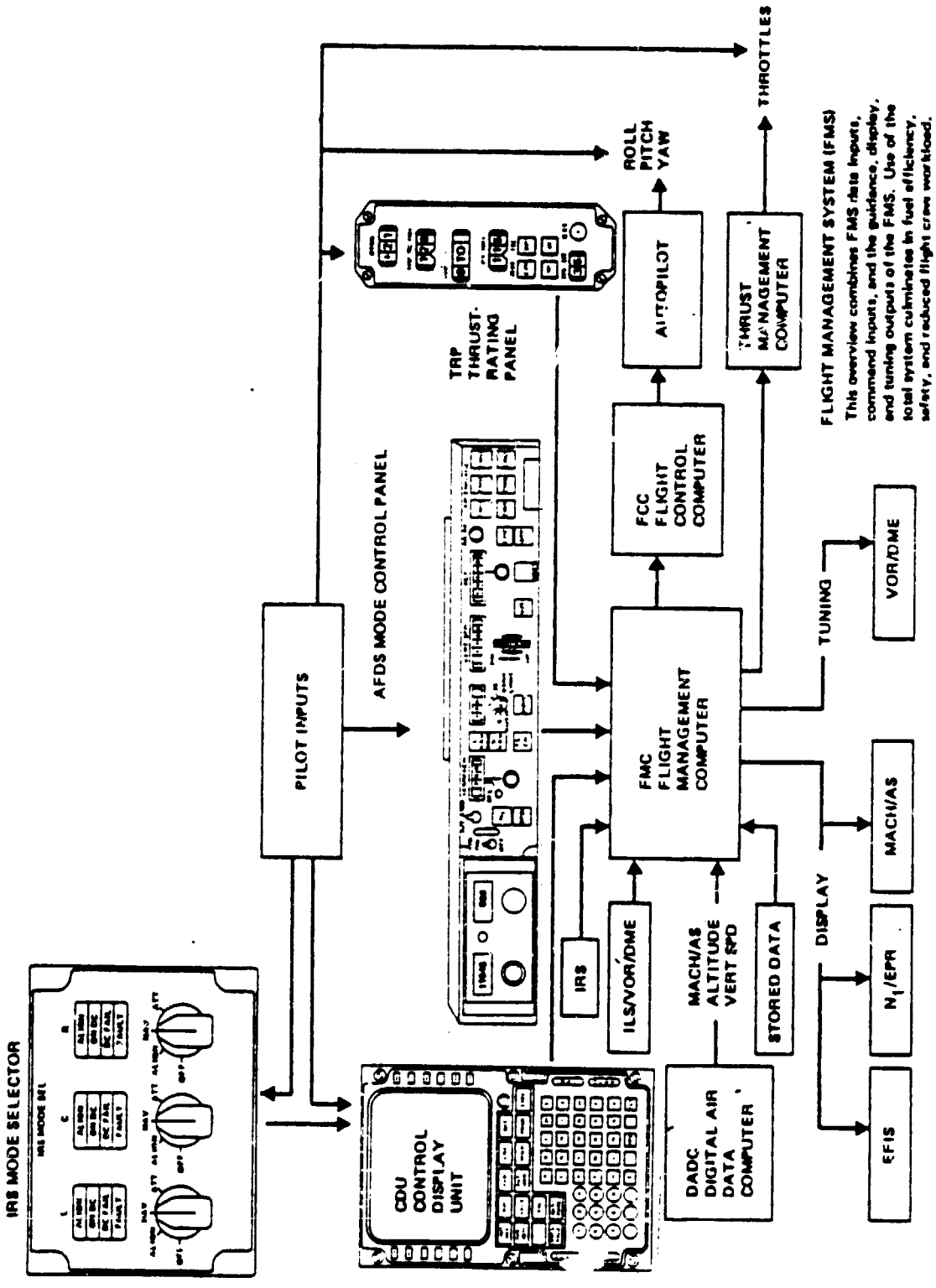

Figure 7.1-1: FLIGHT MANAGEMENT SYSTEM FUNCTIONAL OVERVIEW

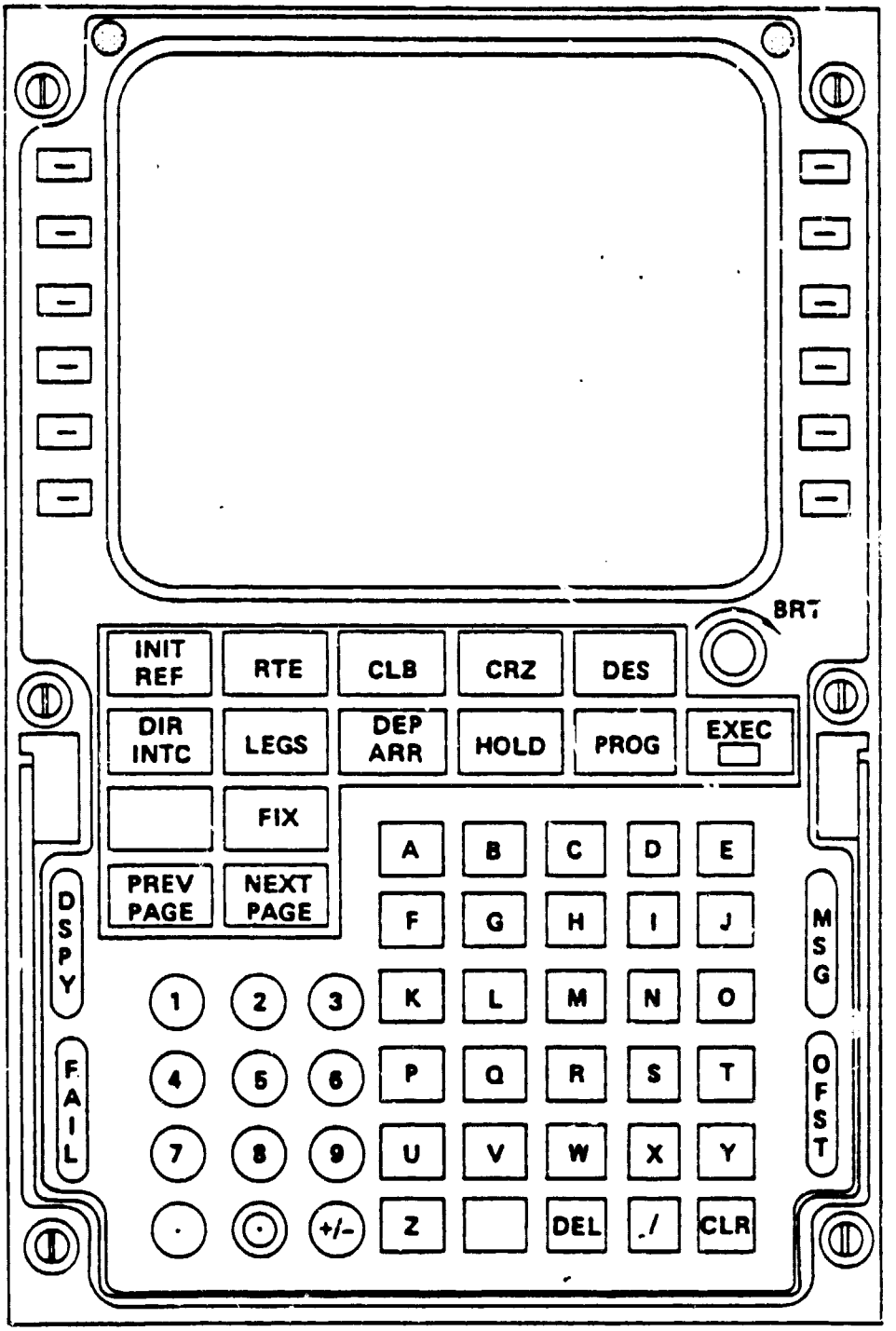

Figure 7.1-2: FMS CONTROL DISPLAY UNIT

flight modes. The other ten keys below the first row perform dedicated functions. An alphanumeric entry is provided at the bottom. The small CRT display displays messages, acts as a scratchpad and displays menu choices. The bezel switches select menu choices and enter scratchpad data. It should be noted that all the keyboard switches are fixed legend, with the bezel switches being the only switches operating with the small CRT, in a multi-function mode.

The system integrates automated flight control, guidance and navigation and aircraft performance management. This combination of functions allows a computer algorithm to be used to achieve an optimum tradeoff between fuel costs and time and to update this solution in flight as route changes are required. The stored navigation data base is tailored to individual airline requirements. Hence depression of DEP/ARR initiates a sequence for quick selection of runway and departure/arrival information specific to that flight. Menu selection is used to minimize operator input; as was discussed in Section 6.3 this approach provides the additional advantage of allowing the operator to proceed with a task sequence based on recognition of items in a list rather than requiring recall of available options from memory.

7.2 Universal Display and Control System (UDACS)

UDACS is a Boeing designed multi-function control system for application in multi-operator airborne surveillance and/or command installations. The system design was intended to be applicable to a wide range of differing installations and functions without major hardware modification. The present design is to be used to update the P-3 aircraft installations used by the Royal New Zealand Air Force on submarine detection and surveillance patrols. Five consoles are to be installed in each of five aircraft. The system is currently in a pre-production testing phase.

Two basic displays form a major portion of the operator-console interface. These are: 1) a stroke-writer CRT which can be either a monochrome or beam penetration type of tube and 2) a flat panel display composed of green LED's with a touch panel overlay. The programmable green LED matrix can be configured as an array of 48 programmable legend switches or a portion of the

area can be used as a 16 x 22 character display area for alerts, cueing or other data. The touch panel overlay uses a crossed X-Y grid of contacts to indicate switch contact, thus fixing the positions available for switch locations.

Each display is directly controlled and refreshed by circuitry associated with a TI 9900 microprocessor. The keyboard and display programming and legends are stored and controlled by an Intel 8086 microprocessor associated with each console. These microprocessors in turn communicate with the host computer over a 1553B data bus. Figure 7.2-1 shows an example of the operator console. Five operator consoles make up a system as installed in the P-3 aircraft. The fixed legend keyboard is used for data entry. The trackball is employed in cursor positioning on the CRT display.

7.3 Partial Systems Examples

The previous two sections described systems in or near production. Several discussions during the survey concerned examples of demonstrations or designs not yet fully implemented. The following subsection describes some of these examples

7.3.1 LCD Keyboard Demonstrator

Research at NASA-Langley is directed in part towards development of a multifunction keyboard (MFK) using a dichroic LCD panel with integrated varactors to enhance the contrast ratio. The panel is manufactured by General Electric and will use a capacitive touch panel overlay to indicate switch activations. When complete, the LCD keyboard will be interfaced to a VAX host computer via a 1553B data bus for MFK operations simulation. Integration with the VAX is anticipated in late 1982 (Reference 7-2).

7.3.2 LED Display Panel

Litton Systems of Canada has developed a green LED matrix display for installation in the F-16 aircraft. The unit will display five lines of 16 characters and be sunlight readable. Display size is 7.5 x 10cm plus bezel editing switches.

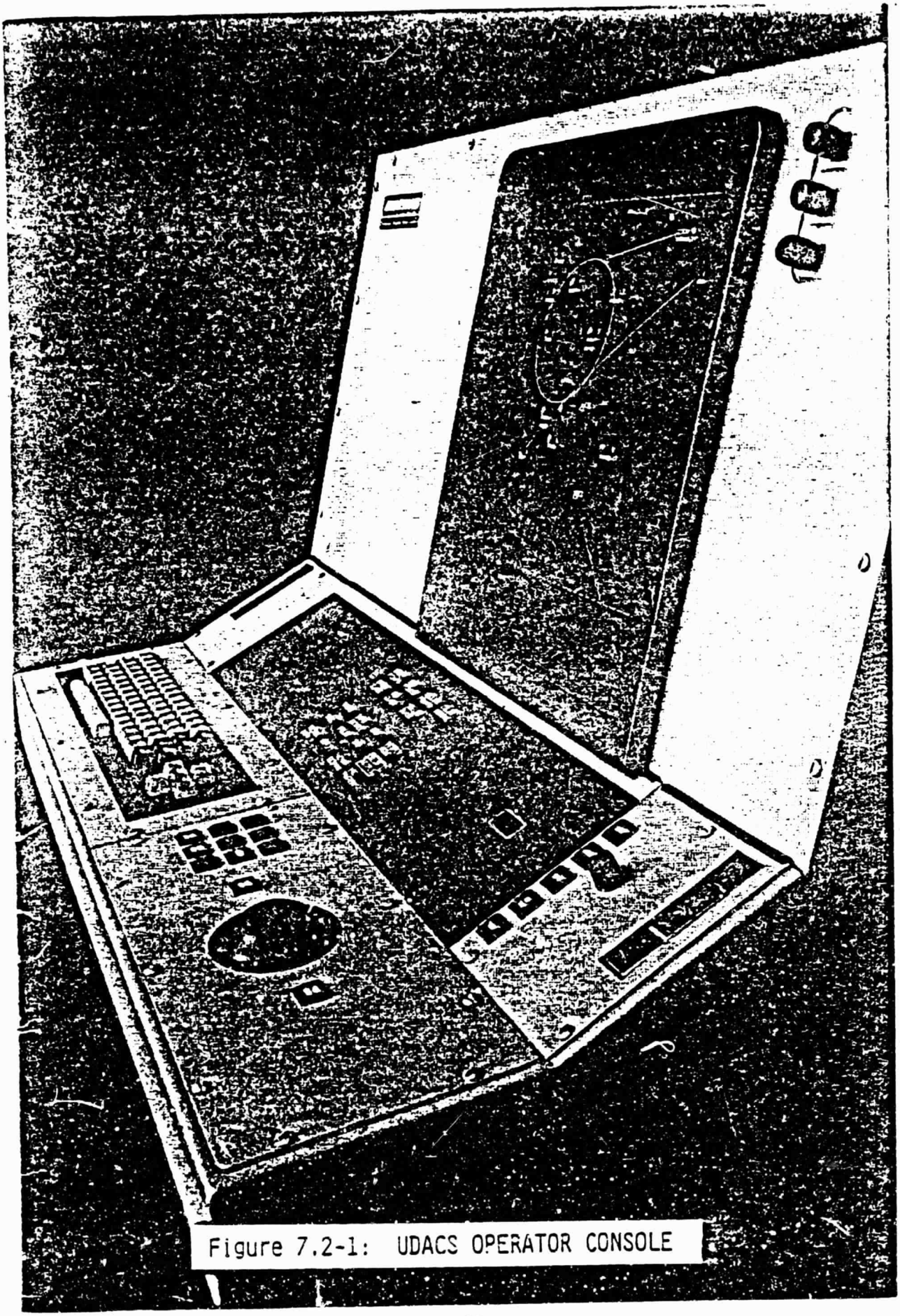

Figure 7.2-1: UDACS OPERATOR CONSOLE

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Combined with a keyset, the display will be used for data entry and operation of communication and navigation equipment. During testing in simulators, F-16 pilots had a good response to the operation of the displays (Reference 7-3).

7.3.3 All-Electronic Flight Deck

The all-electronic flight deck program with Boeing Commercial Airplane Company (BCAC) is developing display, control, and interface technology applicable to future commercial aircraft. The technology demonstration flight deck developed within this program currently incorporates a MFDC unit consisting of a matrix of 20 programmable legend switches, each made up of a single small CRT and a voice input system. The CRT-based programmable legend switches will be replaced during 1982 with an LED-based version developed by BCAC.

8.0 REFERENCES

References are listed below according to the main section of the text in which they occur.

2-1 Jowid, A., IEEE seminar on Space Transportation System, Seattle, Washington, November, 1981.

3-1 Hazeltine presentation of characteristics of IP-1394G Militarized Color Monitor, September, 1981.

3-2 Results of Boeing tests on electrostatic deflection CRT tube for airborne console application.

3-3 Sinclair, C., "Small Flat Cathode Ray Tube", 1981 SID International Symposium, 12, 138, 1981.

3-4 Burnette, K.T. and W. Melnick, "Multi-Mode Matrix (MMM) Flat Panel LED Varactor-Graphic Concept Demonstrator Display", Proc. SID Volume 21/2, 1980.

3-5 Burnette, K.T., "Multi-Mode Matrix (MMM) Display Design and Measurement Criteria", Proc. SID Volume 21/2, 1980.

3-6 Burnette, K.T., A.J. Moffat, and P.G. Wareberg, "Multi-Mode Matrix (MMM) Modular Flight Display Development, Proc. SID Volume 21/2, 1980.

3-7 Niina, T., S. Kuroda, T. Yamaguchi, H. Yonei, Y. Tomida, and K. Yagi, "A Multi-color GaP LED Flat Panel Display Device", 1981 SID International Symposium, 12, 140, 1981.

3-8 Discussion with David Kennedy of Optotek, Canada, November, 1981.

3-9 Discussion with Siemens Component Group, Cupertino, California, December, 1981.

3-10 Toshiba technical literature, Model TLC-651, 1981.

3-11 Hewlett-Packard technical literature, Model HDSP-2000, 1981.

3-12 Spiger, R., "An Evaluation of Dot Matrix Liquid Crystal Displays", Boeing Document D180-26546-1, August, 1981.

3-13 Discussion with P. Brody, Panelvision, Pittsburgh, PA.

3-14 Seattle Times, October 15, 1980, A3.

3-15 Beresford, R., "Thermal Cycling Activates, 'Freezes' Liquid Crystal Display", Electronics, November 30, 1981.

3-16 Allan, R., "Display Technologies Offer Rich Lode for Designers", Electronics, 127, March 13, 1980.

3-17 Gielow, T., R. Holly, D. Lanzinger, and R. Tuttle, "Monolithic Driver Chips for Matrixed Gray-Shaded TFEL Displays", 1981 SID International Symposium, 12, 24, 1981.

3-18 Sharp technical literature, Models S1021A and S1050, 1981.

3-19 Interstate Electronics Corporation technical literature, Model 3000, December, 1981.

3-20 Free, John, "Flat Screen TV", Popular Science, 54, June, 1981.

3-21 Industrial Electronic Engineers technical literature, Catalog FL-1, 1981.

3-22 Iwade, M., K. Kasano, M. Masuda and T. Nakamura, "Vacuum Flourescent Display for TV Video Images", 1981 SID International Symposium 12, 136, 1981.

3-23 Snyder, H.L., "Human Visual Performance and Flat Panel Display Image Quality", Virginia Polytechnic Institute Human Factors Laboratory and Office of Naval Research, Document HFL-80-1/ONR-80-1, 1980.

3-24 Farrell, R.J. and J.M. Booth, "Design Handbook for Interpretation Imagery Displays", Boeing Document D180-19063-1, 1975.

3-25 Burnette, K.T., Multi-Mode Matrix (MMM) Display Design and Measurement Criteria, Proc. SID, 21, 127-142, 1980.

3-26 Semple, C.A., R.J. Heapy, E.J. Conway, and K.T. Burnette, "Analysis of Human Factors Data for Electronic Flight Display Systems", Air Force Flight Dynamics Laboratory Report AFFDL-TR-70-174, 1971.

3-27 Silverstein, L.D. and R.M. Merrifield (Boeing Commercial Airplane Company authors), "Color Selection and Verification Testing for Airborne Color CRT Displays", Fifth Advance Aircrew Display Symposium, Naval Air Test Center, 1981.

3-28 Martin, A., "The CRT/Observer Interface", Electro-Optical Systems Design, 1977.

3-29 Shurtleff, O.A., Legibility research, Proc. SID, 15, 41-51, 1974.

3-30 Bouma, H., "Visual Reading Processes and the Quality of Test Displays", in E. Grandjean and E. Vigliani (ed), Ergonomic Aspects of Visual Display Terminals", Taylor and Francis, London, England, 1980, 101-114.

4-1 Discussion with L. Smilen, Almac-Stroum Electronics. December, 1981.

4-2 Discussion with P. Wehrenberg, Ampex, November, 1981.

4-3 Discussion with D. Huber, Sperry Flight Systems, December, 1981.

4-4 White, R.M., "Disk Storage Technology", Scientific American, 243, 2, 138, 1980.

4-5 "Optical Memory Stores 10^{12} Bits", NASA Tech Briefs 6, 1, 15, 1981.

4-6 Discussion with A. Cosgrove, Boeing, December, 1981.

5-1 Fluke technical information, Model 1780A Infotouch Display, 1981.

5-2 Discussion with W. Smith, Boeing, December, 1981.

5-3 Discussion with L. W. Emo, Microswitch, December, 1981.

5-4 Discussion with D. Basham, Boeing, December, 1981.

6-1 Calhoun, G.L., "Control Logic Design Criteria for Multifunction Switching Devices", Proc. Human Factors Society 22nd Annual Meeting, 383-387, 1978.

6-2 Weiss, W., "Schematic Displays for the Space Shuttle Orbiter Multifunction Cathode-Ray-Tube Display System", NASA-TM-58206, JSC-13853, 1979.

6-3 Calhoun, G.L., E.L. Herron, J.M. Reising, and R.P. Bateman, "Evaluation of Factors Unique to Multifunction Controls/Display Devices", Air Force Wright Aeronautical Laboratory Report, AFWAL-TR-80-3131, 1980.

6-4 Aretz, A.J. and C.J. Kopala, "Automatic Return in Multifunction Control Logic", Proc. Human Factors Society 25th Annual Meeting, 254-256, 1981.

6-5 Geer, C.W., "Analysts Guide for the Analysis Sections of MIL-H-46855", Boeing Document D180-19476-1, prepared for the Naval Air Development Center under Contract N62269-75-C-0271, June, 1976.

6-6 Bedregal, J., "Subsystem Workload Analysis Tool (SWAT) User's Guide", Boeing Computer Services Document BCS-G-0863, Seattle, Washington, 1977.

6-7 Anderson, A.F., "Timeline Analysis (TLA) Program User's Guide", Boeing Commercial Airplane Company Document D6-44751-1, Seattle, Washington 1978.

6-8 Graham, D.K., "A Procedure for the Design of Multifunction Switching Controls", JANAIR Report 740702, 1974.

7-1 Discussion with J. Hatfield, NASA-Langley, December, 1981.

7-2 Discussion with B. Bisley, Litton Systems Canada, December, 1981.

REVISIONS			
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