METRIC

MIL-HDBK-87213
18 December 1996
SUPERSEDING
AFGS-87213B
8 January 1993

MILITARY HANDBOOK

ELECTRONICALLY/OPTICALLY GENERATED AIRBORNE DISPLAYS

AMSC: N/A

AREA: 15GP

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FORWARD

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Beneficial comments (recommendations, additions, deletions) and any pertinent data which may be of use in improving this document should be addressed to: ASC/ENSI, 2530 Loop Road-West, Wright-Patterson Air Force Base, Ohio 45433-7101 using the self-addressed Standardization Document Improvement Proposal (DD Form 1426) appearing at the end of this document or by letter.

This handbook replaces AFGS-87213B, of the same title, and AFGS-87216: Instrument Systems, Airborne. The first section (Controls and Displays Segment Requirements) of this handbook is closely related to the controls and displays requirements in the Joint Services Guide Specification on Avionics Systems. The rest of this document covers requirements applicable to the basic elements of an aircraft control and display (and instrument) subsystem.

Appendix A contains historical reference material taken from AFGS-87216, which dealt mainly with electromechanical instruments. Although many of the issues covered there are now the subject of symbology standards (see MIL-STD-1787), the history of how it was done on mechanical instruments (which many current pilots learned to fly with) can be very valuable.

This document no longer contains the specification sections of the old guide specifications. It does include most of the material from the old guide specification handbooks, including most of the sample specification paragraphs. This material has been updated to include new technical information and lessons learned, and to eliminate references to military specifications and standards that controlled design of equipment rather than dealing only with performance requirements.

TABLE OF CONTENTS

ELECTRONICALLY/OPTICALLY GENERATED AIRBORNE DISPLAYS

HANDBOOK

1.0 INTRODUCTION

1.1 Scope.
This handbook provides sample specification paragraphs, rationale, guidance, and lessons learned that are useful in the development of the primary flight displays and mission avionics controls and displays subsystem for an aircraft. This includes Head-Up Displays (HUDs), Helmet-Mounted Displays (HMDs), and Multi-Function Displays (MFDs), used for presentation of graphics as well as display of TV, FLIR, and radar video, and the associated electronic display generation equipment. Rationale paragraphs explain the reason for specifying each parameter. Guidance paragraphs explain what values are normally used and why. Lessons learned paragraphs serve as a historical information repository for this technical area.

1.2 Use.
This handbook cannot be used as a contractual document. Sample specification paragraphs within this document should be completed using the information in the guidance and lessons learned paragraphs, and may be used in a contract-peculiar item development specification, subsystem specification, or system specification.

1.3 Structure.
This document is arranged to cover topics as they are normally covered in display equipment specifications. It uses the tiered numbering scheme commonly found in government documents with one major exception: Each topic is covered as a package, i.e., the rationale, guidance, and lessons learned paragraphs follow the sample specification paragraph, and the corresponding section 4 (Verification) paragraph follows immediately after the section 3 (Requirement) package.

1.4 Deviation.
This document contains no firm requirements and is not mandatory. In the event that deviation from the guidance herein results in improvement of system performance, reduced life cycle cost, or reduced development cost, or where the requirements of this specification result in compromise in operational capability, the user is encouraged to deviate, with careful consideration of all system tradeoffs. Such deviations should be brought to the attention of the responsible engineering office for consideration of changes to the handbook.

1.5 Responsible engineering office.
The responsible engineering office (REO) for this handbook is ASC/ENAS, Bldg 560, 2530 Loop Road West, Wright-Patterson AFB, OH 45433-7101. Requests for additional information or assistance on this handbook can be obtained from James C. Byrd, DSN 785-8731, commercial (513) 255-8731, fax (513) 255-3466, or EMail: ByrdJC@ASC-EN.WPAFB.AF.MIL. Any information obtained relating to Government contracts must be obtained through contracting officers.

2.0 REFERENCE DOCUMENTS

Documents cited herein are intended to provide supplemental technical data and guidance. Documents referenced in this handbook should be tailored before contractual use. The documents are listed here to provide guidance for developing requirements for specification sections 3 and 4 and program tasking. Section 2, of the contractual specification, should list all documents required for the program. DoD is

Section 2, of the contractual specification, should list all documents required for the program. DoD is currently implementing policy to minimize use of military specifications and standards. Programs should verify status of all the documents listed and/or cited herein before applying them or referencing them in contracts.

(Copies of specifications, standards, handbooks, drawings, and publications required by contractors in connection with specific acquisition functions should be obtained from the contracting activity or as directed by the contracting officer. If no contract has been cited, the source of document availability follows each section.)

2.1 Government documents.
Unless otherwise indicated, the documents specified herein are referenced solely to provide supplemental technical guidance.

2.1.1 Specifications, standards, and handbooks.

SPECIFICATIONS	
MIL-L-85762	Lighting, Aircraft, Interior, Night Vision Imaging System (NVIS) Compatible
AFGS-87235	Emergency Escape, Aircraft
AFGS-87240	Lighting Equipment, Airborne, Interior and Exterior
AFGS-87266	Aircraft Cockpit Transparency System
STANDARDS	
MIL-STD-210	Climatic Information to Determine Design and Test Requirements for Military Systems and Equipment
MIL-STD-461	Control of Electromagnetic Interference Emissions and Susceptibility, Requirements for the
MIL-STD-462	Measurement of Electromagnetic Interference Characteristics, Test Method Standard for
MIL-STD-704	Aircraft Electric Power Characteristics
MIL-STD-1472	Human Engineering Design Criteria for Military Systems, Equipment and Facilities
MIL-STD-1553	Digital Time Division Command/Response Multiplex Data Bus
MIL-STD-1776	Aircrew Station and Passenger Accommodations
MIL-STD-1787	Aircraft Display Symbology
MIL-STD-1801	User/Computer Interface
HANDBOOKS	
MIL-HDBK-1553	Multiplex Applications Handbook
MIL-HDBK-87244	Requirements for the Integrity of Avionics

(Unless otherwise indicated, copies of federal and military specifications, standards, and handbooks are available from the Standardization Documents Order Desk, Building 4D, 700 Robbins Avenue, Philadelphia PA 19111-5094, phone 215-697-2667.)

2.1.2 Other Government documents, drawings, and publications

Unless otherwise indicated, the documents specified herein are referenced solely to provide supplemental technical information and data.

ASC/ENFC 96-01	Lighting, Aircraft, Interior, Night vision Imaging System (NVIS) compatible
AFAMRL-TR-83-095	Optical and Human Performance Evaluation of HUD Systems Design
AFR 161-35	Hazardous Noise Exposure
ASD-TR-83-5019	Optical and Human Performance Evaluation of HUD Systems Design
FAA AC No. 25-1309-1A	System Design and Analysis
FAA FAR-25.1309	Airworthiness Standards, Transport Category Airplanes (Equipment, Systems, and Installation)
FAA-TSO-C113	Airborne Multipurpose Electronic Displays
NAT-STD-3350	Analogue Video Standard for Aircraft System Applications
NAT-STD-3800	Night Vision Goggle Lighting Compatibility Design Criteria
OSHA	Code of Federal Regulations Part 19103

(ASC/ENFC documents may be obtained from ASC/ENFC, Building 560, 2530 Loop Road-West, Wright-Patterson AFB OH 45433-7101.)

(Air Force regulations (AFR), military technical reports (TR) and Occupational Safety and Health Standards (OSHA) may be obtained from the National Technical Information Service (NTIS), 5285 Port Royal Road, Springfield VA 22161)

(Federal Aviation Administration (FAA), Advisory Circulars (AC) , and Federal Aviation Regulations (FAR) may be obtained from the Superintendent of Documents, U.S. Government Printing Office, Washington DC 20402)

(FAA Technical Standard Orders (TSO) may be obtained from the Federal Aviation Administration, Aircraft Certification Service, Aircraft Engineering Division, Technical Analysis Branch (AIR-120), 800 Independence Avenue-SW, Washington DC 20591)

(NAT standards may be obtained from Naval Publications and Forms Directorate (NPFD), 5801 Tabor Avenue, Philadelphia PA 19120-5099)

2.2 Non-Government publications

Unless otherwise indicated, the documents specified herein are referenced solely to provide supplemental technical information and data.

ARINC 725	Electronic Flight Instruments
C.I.E.	Supplement No. 2 to Publication 15 (E-1.3.1), Recommendations on Uniform Color Spaces-Color Difference Equations, and Psychometric Color Terms
EIA-RS-170	Electrical Performance Standards-Monochrome Television Studio Facilities
EIA-RS-343	Electrical Performance Standards for High Resolution Monochrome Closed Circuit TV Camera
EIA-TEPAC-105-9	Line Profile Measurements in Shadow Mask and Other Structured Screen Cathode Ray Tubes
EIA-TEP-116-B	Optical Characteristics of CRTs

RTCA-DO-160	Environmental Conditions and Test Procedures for Airborne Equipment
SAE-ARP-1782	Photometric and Colorimetric Measurement Procedures for Airborne Direct View CRT Displays
SAE-AS-8034	Minimum Performance Standard for Airborne Multipurpose Electronic Displays
SAE-ARP-4256	Design Objectives for Liquid Crystal Displays for Part 25 (Transport) Aircraft

Barten, P. "The effect of glass transmission on the subjective image quality of CRT pictures." In: *Eurodisplay '90 International* Display Research Conference, Amsterdam, September 25-27, 1990, Proceedings. Playa del Rey, CA: Society for Information Display, 1990. Pp. 336-339.

Boff, K. R. & Lincoln, J. E. Engineering Data Compendium, Human Perception and Performance. Wright-Patterson Air Force Base, OH: Harry G. Armstrong Aerospace Medical Research Laboratory, 1988.

Farley, W. "Determination of monochrome display MTFs in the presence of glare." In: SID '89 International Conference, Baltimore, MD, May 1989, Digest of Technical Papers. Playa del Rey, CA: Society for Information Display, 1989. p. 212.

Gard, Jerry. HUDs in Tactical Cockpits. Kaiser Electronics Company, unofficial guidebook, 1989.

Keller, P. and R. Beaton. "The EIA standard for MTFs of monochrome CRTs." In: SID '89 International Conference, Baltimore, MD, May 1989, *Digest of Technical Papers. Playa del Rey*, CA: Society for Information Display, 1989. p. 204.

Kocien, D. F. Design Considerations for Virtual Panoramic Display (VPD) Helmet Systems Design. Neuilly-sur-Seine, France: NATO *Advisory Group for Aerospace Research and* Development (AGARD), 1991. AGARD Conference Proceedings, no. 425.

Post, D. L. "US Air Force color display issues." In: Aerospace Behavioral Engineering Conference, 5th, Long Beach, CA, October 13-16, 1986, *Proceedings*. Warrendale, PA: Society of Automotive Engineers, Inc., 1986, pp. 227-247.

Tannas, Larry. Flat Panel Displays and CRT Displays. New York: Van Nostrand Reinhold, 1985.

(Application for AGARD documents should be addressed to Advisory Group for Aerospace Research and Development, North Atlantic Treaty Organization, 7 rue Ancelle, 92200 Neuilly sur Seine, France)

(Application for ARINC documents should be addressed to Aeronautical Radio, Incorporated, 2441 Riva Road, Annapolis MD 21401)

(Application for EIA documents should be addressed to Electronics Industries Association, 2001 Pennsylvania Avenue-NW, Washington DC 20006)

(Application for RTCA documents should be addressed to RTCA Incorporated, 1140 Connecticut Avenue-NW, Suite 1020, Washington DC 20036)

(Application for SAE documents should be addressed to Society of Automotive Engineers, Incorporated, 400 Commonwealth Drive, Warrendale PA 15096)

(Application for SID documents should be addressed to Society for Information Display, 1526 Brookhollow Drive, Suite 82, Santa Ana CA 92705-5421)

(Technical society and technical association specifications and standards are also generally available for reference from libraries. They are also distributed among technical groups and using Federal agencies.)

2.3 Order of precedence

In the event of conflict between the text of this handbook and the references cited herein, the text of this handbook should take precedence. Nothing in this handbook, however, shall supersede applicable laws and regulations unless a specific exemption has been obtained.

3.0 and 4.0 REQUIREMENTS AND VERIFICATIONS

3.1 Controls and Displays Segment.

The avionic subsystem shall provide for presentation of information and control of functions of the system, including presentation of ___1___. The information displayed shall be fully legible, easily interpreted, and free of distracting artifacts such as flicker, jitter, and noise under all specified environmental, mission and threat conditions. Latency of displayed data shall be limited such that the crew does not perceive a delay between control inputs and the system's response. Redundancy or multiple information paths shall provide for ___2____.

REQUIREMENT RATIONALE (3.1)

The Control and Display (C&D) requirements herein define the Pilot Vehicle Interface (PVI) functions that are performed by the avionic subsystem. C&D is part of the total PVI requirement (which will be specified in other specifications, such as an air vehicle and a crew station specification) and must be integrated with the other parts, e.g. flight controls, escape systems, the canopy, pilot accommodation, internal and external lighting, and the layout of the cockpit.

In the case of a non-manned vehicle, this paragraph would be re-worded to define what C&D data must be collected, processed and transmitted by the avionic subsystem for use by system operators who may be on the ground.

Major system procurements, such as a new aircraft, will generally only have a System requirements document in the initial request for proposal (RFP), and the contractor will be required to submit specifications on each subsystem or unit, either as part of his proposal or as a data item. Procurements for a single unit or a subset of the display system require that the project engineer prepare a separate Technical Requirements Document.

An aircraft or avionics system specification generally includes overall display system functional requirements, as discussed in the following subparagraphs. There will also generally be specifications for the individual elements of the display segment (MFDs, HUD, VCR, etc) broken out according to the contracting structure. These specifications should be based on the detailed specification paragraphs in section 3.2 herein.

REQUIREMENT GUIDANCE (3.1)

This paragraph defines the major functions of the C&D function and establishes that it is expected to work over the full range of missions and environments. "Easily interpreted" means that a minimum of mental interpretation is required, for example, an unknown symbol should not be used if a plain English word will convey the meaning more clearly. Legibility and interpretability can also be aided by making the level of detail tailorable or declutterable.

Blank 1 should describe the major functions to be provided by the C&D element of the avionics subsystem such as:

- Display of Primary Flight Data (PFD)
- Prioritizing and displaying Warning, Caution and Advisory (WCA) data
- Display of mission avionics data, including situation awareness and flight plan information
- Entering or transferring of data
- Recording the results of the mission
- Display of data for other vehicle systems (engines, fuel, etc.).

"Display of mission avionics data" is generally expanded to more specifically state what display modes are required (Helmet mounted, Head up, Multifunction displays, etc.) in the EMD phase, when a specific system concept has been established. More specific requirements and guidance, as might be found in individual display element specifications, are contained in other section 3.2 "characteristics" of this handbook.

The requirements in the second sentence (fully legible, free of artifacts) are somewhat qualitative in nature, but they are important to the flow-down of requirements. The specific luminance, contrast, refresh rate, resolution, etc. requirements in lower level specifications are there to insure that this system-level performance requirement is met.

Blank 2 should describe the level of redundancy expected, if it is not already driven by a more basic mission completion requirement elsewhere in the spec. A typical requirement on the C&D segment would be to retain the capability to present all data in the presence of any single point failure. This requirement would apply to the entire C&D segment, while the separate limitations on the display of hazardously misleading information in the Primary Flight Displays paragraph only applies to displays used as primary flight displays.

REQUIREMENT LESSONS LEARNED (3.1)

Evolution of cockpits has progressed to the point where nearly all C&D functions can be provided with an integrated system of electronic controls and displays, resulting in major savings in the amount of hardware required, while providing the capability of processing and integrating data into the specific information the aircrew needs. The old paradigm called for mission avionic displays separate from flight instruments, propulsion displays and maintenance displays, but this is being proven unnecessary in modern cockpit designs like the F-22 and Boeing 777.

The mission of the aircraft will determine which display functions and characteristics are required. In the early phases of a program, very general guidance will be available in documents such as the Statement of Need and Program Management Direction. Studies, simulations, and meetings with the users must all be used with good engineering judgment to arrive at a suitable set of display requirements.

4.1 Verification of Controls and Displays Segment.

Compliance with the general display requirements of 3.1 will generally become obvious during other tests and inspections. Any other introductory and general quality assurance provisions should also be put into 4.1 They are located here in order to allow all of the remaining paragraphs of section 4 to exactly parallel the section 3 paragraph with the similar number.

[a] Verification of legibility shall be by ______.

[b] Verification of latency shall be by ______.

VERIFICATION RATIONALE (4.1)

Legibility and latency requirements are generally allocated down to individual C&D elements, but must be verified at the C&D subsystem level to establish that the complete system meets requirements.

VERIFICATION GUIDANCE (4.1)

Legibility should be measured against the luminance, resolution and symbology characteristics requirements contained herein and in MIL-STD-1787. Latency can be measured in a laboratory environment. They must also be evaluated by pilot evaluations in simulation and flight tests.

VERIFICATION LESSONS LEARNED (4.1)

Legibility and latency requirements apply to the entire C&D segment. They are often controversial and difficult to measure but are critical to an effective user interface. Ability of the display subsystem to provide essential information to the crew during limited failures is normally planned for and implemented. However, unexpected faults and failure modes have caused a "dark cockpit" situation on more than one prototype airplane.

3.1.1 Primary Flight Displays (PFD).

Primary flight display presentations (as defined in MIL-STD-1787) shall be provided ____1____. Integrity of data presented shall be such that ___2___. Primary flight data shall be clearly legible in all ambient lighting environments, including full sunshine as defined in section 3.2 of this handbook.

REQUIREMENT RATIONALE (3.1.1)

The continuous availability and integrity requirements that apply to primary flight data are significant drivers on the avionic hardware, software and architecture design. They must be made clear at a high level and flowed down into lower tier documents.

REQUIREMENT GUIDANCE (3.1.1)

MIL-STD-1787 defines the information (such as attitude, airspeed, altitude, roll, etc) which must be available in a PFD and defines the standard symbols which should be used. Blank 1) must describe the major characteristics of the PFD, e.g., "head-up, head down, continuously, in both cockpits." Blank 2) establishes the capability of the system in the presence of failures, typically "no loss of function with a single point failure". It should also deal with the probability of presenting bad data, with a requirement such as "the probability of presenting Hazardously Misleading Information (HMI) shall be less than once per 10^{9} flight hours." The data integrity requirements have not been consistently applied, but are important. They should prevent things like the "dark cockpit" which has occurred when all the cockpit displays shut down simultaneously on a certain prototype aircraft (which we will not mention here), resulting in intense design correction efforts to make sure it never happens again.

The traditional approach to guaranteeing that the pilot has valid data available was to provide a separate, independent set of standby instruments, so the pilot always had more than one source for essential information and could therefore usually determine if an instrument was malfunctioning. In an all-electronic cockpit, the "standby" instruments consist of a Flight Display format on another electronic display. The data and power sources for this display must be either completely independent of the primary or be designed with redundancy and integrity that can meet the extreme probabilities associated with HMI.

It should be possible to complete a mission with a single-point failure. This is often possible with a reasonably small amount of redundant hardware and wiring if a degraded mode of operation is allowed. This may require workarounds, such as sharing a display, which increases workload. For flight critical information, a separate, independent system is generally required. For example, in the Combat Talon II display system at least two of the four CRT displays will continue to work and will be capable of displaying any sensor in the event of a single point failure. Many existing aircraft also have backup instruments which will provide adequate data for instrument flight even if the main computers and displays fail. In some new aircraft, which have sufficient redundancy in sensors and power sources to insure that certain displays will continue to operate even with a catastrophic failure of the avionics system, the standby instruments are on an integrated electronic display.

Hazardously Misleading Information is defined as conditions which can result in the display of misleading or false information to the pilot and, as a result, lead to hazardous conditions. These situations should be detected and annunciated if/when they cannot be completely prevented.

HMI situations are generally considered CATASTROPHIC failures since they can result in death and/or loss of the aircraft. A large aircraft or one carrying passengers might require the probability of such an event occurring to have a mathematical probability of 1 x 10^{-9}, or less, per hour of exposure, while small aircraft (including fighter aircraft) might require 1 x 10^{-7}.

The functions considered Safety Critical include, as a minimum, undetected and unannunciated display of hazardously misleading information for the following:

- Altitude indication (includes vertical velocity indication)
- Attitude indication (includes flight path marker, climb dive marker)
- airspeed indication
- Heading indication
- Engine monitor and display
- Fuel quantity indicator

REQUIREMENT LESSONS LEARNED (3.1.1)

Analysis of HMI was carried out in detail on the C-17 with a requirement that the probability of presenting HMI be less than 10^{-10} per flight hour. Their criteria were based somewhat on what the FAA does for airliners. Such strict criteria would not normally be applied to a fighter plane - (if so, we would also need a back-up pilot on board). This requirement had a major impact on the design of hardware and software. For example, the HUD has a second independent processor running completely different software to check results from the main processor to verify that no processing mistakes were made.

The concept of HMI is valuable - it helps us search out and eliminate as many failure modes as possible that have the potential of misinforming or confusing the pilot.

The need for a fail-operational or at least fail-safe design has always been recognized for primary flight displays. Fortunately, current improvements in electronic technology are making this easier to achieve.

Redundant or backup modes must be tested periodically; otherwise they may not work when needed.

4.1.1 Verification of Primary Flight Displays.

[a] Location and availability of PFDs shall be evaluated by inspection.
[b] Data integrity shall be verified by test and analysis.

VERIFICATION RATIONALE (4.1.1)

PFDs are critical to the safety of flight and must be verified. Verification methods will depend on the level of redundancy required and the criticality of the fail-operational performance. In some systems, simply disconnecting certain units or signals will be adequate to demonstrate the effects of failure. In a more complex or critical system, a failure mode effects analysis coupled with a thorough demonstration with a large number of simulated failures will be needed.

VERIFICATION GUIDANCE (4.1.1)

Redundancy requirements and verification may be integrated with a safety analysis, where the probability of a failure which results in a hazardous event is assessed and controlled. FAA FAR part 25, Section 25.1309 and AC No. 25.1309-1A provide guidance on probabilities of failure which should be achieved for functions which have minor, major, or catastrophic consequences. MIL-STD-1787 contains additional data on the design of PFDs.

VERIFICATION LESSONS LEARNED (4.1.1)

Tests and analysis to verify the data integrity requirements are somewhat subjective. For example, it might be assumed that most mistakes (99/100ths??) made by a digital processor will result in displayed data that is either wrong for only one display cycle and therefore disappears before the pilot sees it, or is sufficiently illogical that the pilot will not try to use it. This factor attributed to pilot interpretation can make the difference between a reasonable requirement and an impossible requirement.

3.1.2 Situation Displays.

The C&D segment shall be capable of processing available data into a Situation awareness Display (SD) presentation that presents the aircraft's situation relative to the flight plan, targets, threats, other air traffic and __1__. The C&D segment shall be capable of overlaying this graphic image on video images from __2__. The size and number of displays shall be adequate for simultaneous display of __3__.

REQUIREMENT RATIONALE (3.1.2)

The requirement to provide a real-time graphics image that integrates information from the various sensors and data sources in the system is a major driver on the design of the C&D hardware and SW, and must be established at the Avionic subsystem level. The complexity of this format ranges from a simple plan view of the flight plan on a trainer aircraft to a complete tactical situation display on a fighter or bomber.

REQUIREMENT GUIDANCE (3.1.2)

This paragraph should be modified to cover any displays unique to the mission of the system being developed. This capability may be called by other names such as Horizontal Situation Display (HSD), Tactical Situation Display (TSD), plan view display, etc.
Blank 1) should describe requirements on the situation awareness display, such as a requirement to provide full legibility in sunshine for front cockpit displays and the ability to declutter to various levels, as well as variations on the SD such as specialized offensive and defensive formats. It should also establish the level of background map information to be provided, which may vary from a "stick map" of the flight plan to a full raster image of a detailed map. A detailed moving map image requires a large digital data base and a high performance graphics rendering processor.
Blank 2) should establish requirements to display sensor video (versus computer generated graphics) as appropriate for the sensors in the system, such as radar, moving map, weapons video, FLIR, or TV camera video.
Blank 3) should describe the performance capability (such as simultaneous presentation of PFD, Warnings Cautions and Advisories (WCA) display, Vehicle Management System (VMS) display, and SD) which will drive the size and number of displays needed.

REQUIREMENT LESSONS LEARNED (3.1.2)

The information update rate and screen refresh rate needed to make symbols appear to move smoothly and not flicker is often controversial, and depends on many factors including the type of information being displayed. The Update rates range from once every few seconds for a slow moving symbol on a SD to 50 Hz minimum for the highly dynamic attitude indicator presentation. A refresh rate of at least 60 Hz is needed to prevent visible flicker.

4.1.2 Verification of Situation Displays.

Verification of situation displays capability shall be by demonstration.

VERIFICATION RATIONALE (4.1.2)

The ability to properly display mission information is critical to the mission and must be verified.

VERIFICATION GUIDANCE (4.1.2)

The major C&D features required by this paragraph will be demonstrated repeatedly in simulations and flight tests.

VERIFICATION LESSONS LEARNED (4.1.2)

3.1.3 Head Up or Helmet Mounted Displays (HUD/HMD).

Head Up (HUD)/ Helmet Mounted Display (HMD) capability shall be ___1___. Field of View shall be ___2___.

REQUIREMENT RATIONALE (3.1.3)

The requirement to provide head-up information, with symbology conformal to the real world outside, is critical to certain missions and must be established at the Avionic subsystem level.

REQUIREMENT GUIDANCE (3.1.3)

Blank 1) should state the major requirements on the HUD, such as presentation of a PFD and aiming information for missiles, gun, bombs, cargo air drop, etc., and/or night pilotage video that must be referenced to the real world.

Blank 2) should establish the required field of view, which is typically around 20 degrees for a conventional HUD and may be as wide as 30 degrees for a HUD used with video for night pilotage. A requirement for head-up presentations outside the HUD FOV (e. g., launch of high off-boresight angle missiles) may drive requirements for a Helmet Mounted Display (HMD). Additional guidance on HUD and HMD is found in section 3.2 of this handbook.

REQUIREMENT LESSONS LEARNED (3.1.3)

4.1.3 Verification of HUD/HMD.

Verification of HUD/HMD capability shall be by demonstration.

VERIFICATION RATIONALE (4.1.3)

The ability to properly display mission information is critical to the mission and must be verified.

VERIFICATION GUIDANCE (4.1.3)

The major HUD features will be demonstrated repeatedly in simulations and flight tests. Specific requirements such as field of view should be measured in tests.

VERIFICATION LESSONS LEARNED (4.1.3)

3.1.4 Vehicle Management Subsystem (VMS) Displays.

The C&D segment shall provide for processing and display of VMS and utilities subsystem data, including propulsion, hydraulic, flight control, electrical power and ___1___ data. Subsystem fault lists (for use in-flight and in maintenance) and fault history lists (for use in maintenance) shall be derived from BIT data and presented on ___2___.

REQUIREMENT RATIONALE (3.1.4)

Ability to display data from the "non-avionic" subsystems on the aircraft must be specified if a truly integrated system, without separate displays for each subsystem, is to be built.

REQUIREMENT GUIDANCE (3.1.4)

The first sentence, and blank 1) should be adjusted to reflect the level of integration intended. With modern display processors and a system interconnected by digital data busses, there is no reason to provide separate displays for VMS functions when the information can be processed and presented on the same display units as the mission avionic information.

Blank 2 must establish requirements for display of fault data, typically divided into a fault list to be used by the pilot to determine the operational capability of aircraft systems, and more detailed lists of BIT reports (including history) to be used by maintenance personnel for fault detection and isolation.

REQUIREMENT LESSONS LEARNED (3.1.4)

Built In Test (BIT) has a notorious reputation for being unreliable, generating false alarms, and being difficult to interpret. Use of the avionic display processor and display to sort ("filter") and present the data can make the data much more useful. Using plain text or at least decipherable acronyms rather than "maintenance codes", makes the BIT data much easier to interpret.

The original design of a current fighter included two smaller "VMS" displays, unique from the Multi Function Displays (MFD) used by the avionic subsystem. A trade study revealed that adding one more MFD, and eliminating the two smaller displays resulted in a large life cycle cost savings. It also improved the capability of the system because it made the VMS format larger and easier to interpret and provided the flexibility to locate any format on any display.

4.1.4 Verification of Vehicle Management Subsystem (VMS) Displays.
Verification of VMS display capability shall be by demonstration.

VERIFICATION RATIONALE (4.1.4)

The ability to properly display VMS and utilities information is critical to flight and must be verified.

VERIFICATION GUIDANCE (4.1.4)

The C&D features required by this paragraph will be demonstrated repeatedly in simulations and flight tests.

VERIFICATION LESSONS LEARNED (4.1.4)

3.1.5 Warning, Caution, and Advisory (WCA) Displays.
The avionic subsystem shall provide an integrated prioritization, control, presentation and logging of WCA information. This function shall include ____________. The WCA presentation on electronic displays shall be in addition to any dedicated cockpit annunciator lights for warning and caution.

REQUIREMENT RATIONALE (3.1.5)

Collecting, prioritizing, displaying, controlling and logging WCA information is a critical function of the C&D segment in most aircraft.

REQUIREMENT GUIDANCE (3.1.5)

The WCA function should include processing of BIT and status data to insure that all appropriate WCAs are displayed clearly and promptly, and that false alarms are less than some established maximum.

MIL-STD-411 contains specific design requirements that have been applied to most existing aircraft. While MIL-STD-411 is no longer referenced as a firm requirement, it provides excellent guidance, such as:

a) Warnings are red, cautions are yellow, advisories are green

b) Warnings are life- or aircraft-threatening emergencies and cannot be shut off until the problem is resolved

c) Cautions indicate risk of injury or equipment damage if action is not taken. The master caution indicator can be shut off, but the status of the caution must be continuously displayed.

d) Advisories provide information that may be important to the mission, but is not significant to safety or equipment damage.

REQUIREMENT LESSONS LEARNED (3.1.5)

The WCA function should be clearly identified at the system level, with performance requirements in the avionic subsystem spec. This can prevent the following problems that have occurred:

a) a single hardware failure generates multiple advisories.

b) advisories are issued for things the pilot does not care about, such as a redundant system that re configures around a problem, when there is nothing the pilot should or could do about it.

c) important warnings or cautions that are not immediately apparent because several trivial advisories are cluttering the display.

d) false alarms.

The intent is to sort and integrate the information in such a way that WCAs are always issued to the pilot when needed and only when they are useful, i.e., when some capability has been effected or some pilot action is needed. Some WCA implementations have used BIT failures and other indications of problems from each subsystem on the aircraft to generate WCAs to the pilot with little integration or regard for what the pilot can or should do about them.

False alarms are not only irritating to the crew, but degrade crew effectiveness. The crew becomes accustomed to punching the WCA off and casually trying to verify that it is a false alarm, rather than taking the action necessary assuming it is a real emergency.

4.1.5 Verification of Warning, Caution, and Advisory (WCA) Displays.
Verification of WCA display capability shall be by demonstration and analysis.

VERIFICATION RATIONALE (4.1.5)

The ability to properly prioritize, control, present and log WCA information is critical to flight and must be verified.

VERIFICATION GUIDANCE (4.1.5)

The major WCA features required by this paragraph will be demonstrated repeatedly in simulations and flight tests. Numerical requirements, such as false alarm rate, shall be verified by collecting and analyzing a data base on the WCAs issued by the system.

VERIFICATION LESSONS LEARNED (4.1.5)

3.1.6 Avionic Subsystem Control and Data Entry.

The C&D segment shall provide for control of the various modes and capabilities of the avionic subsystem. The C&D segment shall provide for input of alphabetic and numeric data. Controls shall be designed for ease of use throughout the mission environment and shall __________.

REQUIREMENT RATIONALE (3.1.6)

The C&D segment must provide for control and input of data to the avionic subsystem.

REQUIREMENT GUIDANCE (3.16)

Controls for all avionic modes and functions must be provided. These controls are often in the form of "bezel keys" on the periphery of the displays, similar to the ones used on automated teller machines. The logical arrangement of control functions on the various formats and displays must be developed with direct inputs by human factors engineers and pilots, typically in a crewstation working group. The controls are generally required to provide tactile feedback so that a person can tell when a button has "clicked," even with gloves on.

A keypad is also required in order to enter numbers and letters for communication and navigation systems. It should be a full alpha and numeric keypad (rather than a numeric keypad with alpha characters accessed by multiple shift keys) if editing of flight plan way points in flight is required.

REQUIREMENT LESSONS LEARNED (3.1.6)

MIL-STD-1472 and MIL-STD-1776 provide detailed guidance on the design, function, and location of controls.

4.1.6 Verification of Avionic Subsystem Control and Data Entry.

Verification of avionic subsystem control and data entry capability shall be by demonstration and analysis.

VERIFICATION RATIONALE (4.1.6)

The ability to control all avionic subsystems and enter data is critical to the mission and must be verified.

VERIFICATION GUIDANCE (4.1.6)

The major features required by this paragraph will be demonstrated repeatedly in simulations and flight tests. Specific requirements, such as the requirement for tactile feedback, shall be verified by demonstration or analysis.

VERIFICATION LESSONS LEARNED (4.1.6)

3.1.7 Video Recording.

The C&D segment shall include the capability to record the imagery from ___1___ displays. The recording media shall be accessible to the pilot, easily inserted and removed and no larger than ___2___.

REQUIREMENT RATIONALE (3.1.7)

Most combat aircraft include a video recorder that records information from one or more displays in the cockpit. This recording is used for debriefing, damage assessment, and training.

REQUIREMENT GUIDANCE (3.1.7)

Capability on current aircraft ranges from none to the ability to record 4 displays simultaneously on a single two-hour 8 mm tape cassette. Fighter plane systems generally include a video camera mounted on the HUD to record the scene as viewed through the HUD by the pilot. Additional guidance is found in section 3.2 of this handbook.

REQUIREMENT LESSONS LEARNED (3.1.7)

Commercial video cassette tape transports have been successfully packaged and shock mounted for use in the aircraft cockpit environment. The relatively good performance and low cost of these units represent an excellent example of the savings that can be achieved with modified off-the-shelf and commercial hardware.

4.1.7 Verification of Video Recording.

Verification of video recording capability shall be by demonstration and analysis.

VERIFICATION RATIONALE (4.1.7)

The ability to record mission data on a compact and transportable media is important to the mission and must be verified.

VERIFICATION GUIDANCE (4.1.7)

The major features required by this paragraph will be demonstrated repeatedly in simulations and flight tests. Specific requirements, such as record time, shall be verified by test or by analysis of design data.

VERIFICATION LESSONS LEARNED (4.1.7)

3.2 Characteristics of subordinate elements.

4.2 Verification of characteristics of subordinate elements.

3.2.1 Performance environments.

The following performance requirements shall be met under the full range of environmental conditions specified herein except ___________.

REQUIREMENT RATIONALE (3.2.1)

This paragraph defines the conditions under which the performance requirements in the following subparagraphs are to be met.

REQUIREMENT GUIDANCE (3.2.1)

Performance requirements are generally met over the full range of environments specified, except degraded performance may be allowed during gunfire vibration. Other exceptions are sometimes appropriate, such as allowing deviations from full brightness, speed, or accuracy during the first 5 to 15 minutes after turning on at cold temperature extremes.

REQUIREMENT LESSONS LEARNED (3.2.1)

4.2.1 Verification of performance environments.
Compliance shall be verified as specified herein.

VERIFICATION RATIONALE (4.2.1)

Performance requirements must be verified over appropriate environmental conditions.

VERIFICATION GUIDANCE (4.2.1)

Compliance can be verified by evaluation of test plans and procedures. Extensive guidance on the measurement of photometric and colorimetric characteristics is provided in SAE-ARP-1782.

VERIFICATION LESSONS LEARNED (4.2.1)

3.2.1.1 Reserved.

4.2.1.1 Reserved

3.2.1.2 Lighting color.
Control panel lighting shall ___________. Emitted light shall be compatible with ___________.

REQUIREMENT RATIONALE (3.2.1.2)

Color of display presentations and panel lighting must be controlled for consistency and, in some cases, to insure compatibility with night vision goggles.

REQUIREMENT GUIDANCE (3.2.1.2)

The appropriate panel lighting requirements should be inserted. For many existing aircraft, integrally illuminated panels, with either white or green illumination are used. AFGS-87240, Lighting Equipment, Airborne, Interior and Exterior, should be used to develop the system lighting requirement. On aircraft where the crew will use night vision goggles (NVGs), the spectrum of all emitted light must be closely controlled. (See Section 3.2.1.9) The goal is to prevent excessive red and infrared light from the cockpit from being sensed by the NVGs, causing their sensitivity to the extremely dim outside scene to be reduced.

AFGS-87240 and ASC/ENFC 96-01 define requirements for measuring energy which the NVGs are sensitive to ("NVIS Radiance" or NR) and specify the color and NR content allowed for NVG crewstation equipment. There is also a NATO document (NAT-STD-3800) which covers a similar set of NVG compatibility criteria. If NVG compatibility is required, a measurable definition of compatibility must be put in the specification; for example, "as defined in ASC/ENFC 96-01."

Some systems (particularly Army) have a requirement for "secure lighting". Secure lighting is designed to eliminate near-IR radiation (700-1100 nm) as far as possible and minimize radiation of visible light by making lights green (peak eye sensitivity), only using lights where required for the mission, and making lights dimmable. Secure lighting is important for systems which may be exposed to hostile ground troops who now use NVGs and other Image Intensification (I^2) devices.

REQUIREMENT LESSONS LEARNED (3.2.1.2)

Lighting color tolerances of ± 0.02 x and y units (CIE 1931 color system) were used in the past but were restrictive, especially in the green part of the spectrum. The new colors defined in ASC/ENFC 96-01 for use in night vision compatible cockpits use larger tolerances (for example, a radius of 0.037 for NVG green in CIE 1976 u' v' coordinates). This tolerance is easier to meet, but allows colors which are different enough to be noticeable if they are physically close together and are reasonably bright. In the past, many programs specified the technology to be used (e.g., electroluminescent or incandescent) in order to achieve more uniform color, brightness, and aging characteristics.

On the HH-60, it was required that less than one percent of the CRT display's total light output would be in the spectral range beyond 600 nanometers (red and infrared). This was achieved with monochrome CRTs using P-43 phosphor and a narrow bandpass green filter. While this proved to be operationally compatible with Class A NVG devices, the emissions were higher than allowed by ASC/ENFC 96-01 (requirements similar to MIL-L-85762).

4.2.1.2 Verification of lighting color.

Compliance shall be verified by ___________.

VERIFICATION RATIONALE (4.2.1.2)

Color of lighting must be verified to assure that it is uniform and aesthetically pleasing, and in some cases to assure that it is compatible with night vision imaging systems.

VERIFICATION GUIDANCE (4.2.1.2)

Instrumental verification of lighting color can be accomplished in several ways. Measurements with a spectral radiometer are the most accurate, but the measuring systems are expensive and require considerable user expertise. For P-43 CRTs and other spectrally concentrated sources, radiometric measurements are the only reliable means of color determination. This includes other phosphor-lighted displays as well, including flat panel liquid crystal displays illuminated by fluorescent lamps.

Other means of verification have been developed, tailored to specific lighting schemes. For example, Air Force Blue-Filtered White Light and Instrument Panel Lighting (IPL) White light color measurements can be performed using a properly calibrated four-filter colorimeter (photometer) as the measuring device. This technique works well for filtered incandescent technology because energy is measurable through each of the four tri-stimulus color matching functions (filters in the photometer), and the mathematics are straightforward and easy to use. This technique does not work well if energy is not measurable through each of the four filters. A second example is the ratiometric method of measuring Instrument Panel Lighting (IPL) Red, Aviation Red, and Identification Red light to be a minimum saturation level when compared to a calibrated National Bureau of Standards (now the National Institute of Standards and Technology NIST) red limit filter.

When color is relatively consistent from unit to unit, a visual comparison with a reference standard is often used in production acceptance tests to minimize cost. Visual tests are quick and low cost, and have high probability of success when the standard is close to the nominal requirement for color, the standard is the same physical size as the device under test, and the inspector is light adapted suitably for the task at hand. Visual tests are necessarily subjective, so it is important to have an objective test specified as a backup to resolve any disputes. Additional guidance is found in MIL-L-87240, ASC/ENFC 96-01 and MIL-P-7788

VERIFICATION LESSONS LEARNED (4.2.1.2)

3.2.1.3 Symbology.

The equipment shall be capable of generating and displaying each of the symbols shown and described in __________. All of the symbols in figure __________ shall be displayable simultaneously at sufficient update rate to prevent visible jerking and sufficient refresh rate to prevent flicker. The equipment shall be capable of generating:

[a] ____________ polygons

[b] ____________ layers of occlusion

[c] ____________ flashing symbols

[d] ____________ shadowing (for contrast enhancement)

[e] ____________ colors

[f] ____________ *alphanumeric characters*

REQUIREMENT RATIONALE (3.2.1.3)

For equipment which generates and displays symbology, the symbology characteristics must be specified.

REQUIREMENT GUIDANCE (3.2.1.3)

An appropriate symbology set must be established and documented, usually in a series of figures within the specification or in a separate cockpit design description document resulting from simulations, pilot inputs, etc. MIL-STD-1787, Aircraft Display Symbology, has been widely coordinated and should be used as far as possible. Symbols used in existing systems should be used as far as possible, with consistent meanings, since this minimizes retraining and can prevent fatal confusion in emergencies.

MIL-STD-1787 has specific requirements on primary flight symbology.

Display processor performance in terms of the number of polygons it can process, the number of occlusion layers, etc. is relatively new, and it is not clear what requirements are appropriate for the various types of aircraft displays.

A Helmet Mounted Sight (HMS) or Helmet Mounted Display (HMD) has the unique ability to display symbols over the entire field of regard of the system (up to pi steradians, i.e., all directions), and can present them stabilized (fixed) relative to the earth, relative to the aircraft, or relative to the pilot's head.

Symbols that are calculated using backup or reversionary sources (such as calculating the velocity vector from air data when inertial data input is lost) should be clearly indicated to the pilot.

Symbols that are incorrectly positioned because of field of view (FOV) limitations should be clearly indicated to the pilot. Particular care should be taken so that two symbols which are positioned relative to each other do not change this relationship when placed at or near the limit of the FOV. An example would be a flight director and the Flight Path Marker symbols on a HUD. When the Flight Path Marker is limited by the FOV limit, this should not affect the position of the director steering symbol relative to the Flight Path Marker. This might be accomplished by limiting the Flight Path Marker slightly inside the FOV limit so the director could move around it.

The use of flashing symbols to indicate degraded or FOV-limited data is not acceptable by itself. Flashing symbols are discouraged except for critical alerting functions, such as a breakaway cross.

HUD symbology must be "compatible" with the head-down display (HDD) information.

Symbols that can be deleted by declutter should have a secondary warning when they are deleted because of faulty data. An example might be the annunciation "DATA DELETED" in place of the data if such a symbol is deleted because of invalid data.

REQUIREMENT LESSONS LEARNED (3.2.1.3)

Current trends in electronics have made it generally easy to build symbol generators to be programmable; therefore, it is often not necessary to accurately describe symbol shapes and details before equipment design. The advantage of trying to define the symbol set early is that it allows a reasonable estimate of the number and complexity of the symbols to be made, which is essential to the person attempting to size the symbol generator and make an accurate proposal. Once a symbol set has been chosen, changes to it will generally affect memory and processing requirements on a stroke-by-stroke basis rather than symbol-by-symbol.

While many existing systems have a separate symbol generator unit, some have the symbol storage and/or generation built into the display unit or the central computer. If this can be done without creating complex interfaces or excessively large boxes, it can reduce the total amount of hardware.

People seem to enjoy inventing symbols and will often come up with new and unique symbols if given the chance. The documentation and training problems created by this can be spectacular, so it is essential that the symbol set be based on existing standards and systems.

It is important that appropriate resolution and accuracy of scales be chosen. For each parameter, the resolution must be appropriate for aircrew needs. For example, oil quantity displays can be very coarse, because usually the aircrew is only interested in knowing if the tank is full or close to empty. Increments of 1/4 of a full tank are adequate. On the other hand, engine temperature is critical to the aircrew, so the scale must have much greater resolution and accuracy. Sometimes, as with normal operating engine RPM, the accuracy need is greater over certain portions of the range. In such cases, the scale may be expanded over those portions which require close control. Guidance on this subject can be found under the discussion of individual instruments in the Appendix. In general, the systems application will dictate the accuracy required.

4.2.1.3 Verification of symbology.

Capability to display each of the required symbols shall be visually checked. Details on symbol dimensions and tolerances shall be verified by analysis, visual inspection, and measurement of a representative sample (see 4.2.1.3.1).

VERIFICATION RATIONALE (4.2.1.3)

Proper symbology capabilities must be verified.

VERIFICATION GUIDANCE (4.2.1.3)

Visual checks and symbol measurements are usually used for verification.

VERIFICATION LESSONS LEARNED (4.2.1.3)

3.2.1.3.1 Symbol size and movement.

Alphanumeric symbols shall be at least __________ mm high by __________ mm wide. The symbology shall be capable of a minimum displacement of __________.

REQUIREMENT RATIONALE (3.2.1.3.1)

Minimum size of symbols is specified to insure readability under all conditions. Minimum line movement must be specified to assure that symbols appear to move smoothly.

REQUIREMENT GUIDANCE (3.2.1.3.1)

The following size/resolution relationships should be met. They are based on numerous human factors studies, successful operational systems, and the need to achieve fast, accurate reading under a variety of ambient and stress conditions. Note: sixty minutes of arc = one degree, 17.45 milliradians (mr) = one degree, 3.44 minutes of arc = 1 mr. Size in degrees = arctan(symbol size/viewing distance).

a) Stationary or non rotating raster or matrix display alphanumeric symbols shall subtend a minimum of sixteen minutes of arc and consist of a minimum of sixteen scanning lines or pixels of symbol height and twelve horizontal resolution elements for symbol width .

b) Raster or matrix display alphanumeric symbols oriented other than vertically, and other video shapes shall subtend a minimum of twenty-two minutes of arc and consist of a minimum of twenty horizontal scanning lines for symbol height and twenty horizontal resolution elements for symbol width. This does not apply to raster symbols such as small circles, tick marks, scales, and indices that are in compliance with the symbology requirement.

c) Stroke-written alphanumeric symbols should subtend a minimum of sixteen minutes of arc.

d) Stroke-written alphanumeric symbols on a HUD should subtend a minimum of twenty-four minutes of arc vertically and fourteen minutes of arc horizontally. HUD characters are larger because:

1) They generally represent flight- or mission-critical information.

2) Many of them move and/or rotate.

3) They are overlaid on a real-world background, which may include distracting details.

e) Color symbols must be larger if color coding is important. Studies have shown the need for larger symbols to allow color identification from among six possible colors.

The design eye point in most cockpits is normally around 71 cm (28 inches) from the primary flight displays. At that distance the size of an alphanumeric sixteen minutes of arc in height and twelve minutes in width will be 3.3 x 2.6 mm. If sixteen horizontal scan lines are required for a raster symbol then the display will require forty-eight lines per cm if the smallest acceptable symbols are chosen. On a display with lower resolution than this, the symbols should be made correspondingly larger to avoid the situation where artifacts (notches, raster line gaps) are a significant part of the size of the character.

Larger characters will be readable at lower luminance and contrast (see the scaling factors on Table II, Section 3.2.1.6.3). Many displays use more than one font size. Critical information that must be read during emergencies (e.g., airspeed and altitude) generally uses the largest font, while information that is read in routine situations (e.g., maintenance BIT data) uses the smallest font.

One system which was well accepted by pilots used 875-line (808 active lines) alphanumerics and symbology overlaid on sensor video on a 17 cm (6.8 inch) square CRT. Alphanumerics were twenty-six raster lines high (approximately 5 mm or 0.2 inch high) and subtended twenty-three minutes of arc at the normal viewing distance.

A minimum increment of movement of one-half line width has been used for a HUD. Increments this small or smaller will allow symbols to appear to move smoothly. Raster symbology generators normally store symbol information in a memory matrix map of pixels (for example 512 x 512 for 525-line video, 808 x 808 for 875-line video, 512 x 1024 for high resolution 525-line video, or 640x480 for VGA), and each pixel represents the minimum line movement. Text-type alphanumerics (those that do not rotate or move around the screen with the symbols) are often constrained to appear only in fixed "character cells" and need not meet the minimum movement criteria. (See also 3.2.1.3.3, Guidance.)

REQUIREMENT LESSONS LEARNED (3.2.1.3.1)

Raster alphanumerics and symbology having horizontal lines only one raster line thick will flicker noticeably in a conventional 30-frame/60-field per second interlaced raster. This problem can be reduced by making all lines at least two raster lines thick, or using a 60-Hz non-interlaced format. A non-interlaced format will allow the use of pixels only one raster line high, allowing thinner lines to be drawn, but requires twice the video band width, and makes the video incompatible with standard TV sets and VCRs.

4.2.1.3.1 Verification of symbol size and movement.

Symbol size and minimum line movement capability shall be verified by measurement or design audit.

VERIFICATION RATIONALE (4.2.1.3.1)

Symbol size and minimum movement must be verified to assure that symbols are easily readable and move smoothly.

VERIFICATION GUIDANCE (4.2.1.3.1)

On head-down displays, such as CRTs, it is generally easy to make approximate measurements of symbols on the display with an ordinary ruler. Where parallax errors are large (due to a thick face plate) or accurate measurement of small detail is required, an inspection microscope with a built-in scale can give much better accuracy. For a HUD, a theodolite (a telescope with reticle and calibrated pivot base, like a surveyor's transit) is used. It is not necessary to measure symbols if their size can be verified from other fixed characteristics, such as the number of raster lines per symbol height or a fixed array of pixels.

VERIFICATION LESSONS LEARNED (4.2.1.3.1)

Symbol dimensions can be verified by analysis and one-time gain measurements. Current symbol generators use digital techniques and precision digital-to-analog converters to generate accurate deflection and video wave forms for symbology. If the symbol is programmed correctly, and all analog gains are correct, the symbol will be displayed correctly. If the gains are incorrect, all the symbols will be the wrong size, so measurement of a known vector in X and Y for accuracy and comparison with the rest of the screen is adequate.

3.2.1.3.2 Symbology freeze.

The symbology shall not lock up or freeze when incoming data is changing except in special cases where a symbol is intentionally frozen. If a lockup or freeze occurs, that symbol shall be __________.

REQUIREMENT RATIONALE (3.2.1.3.2)

Important flight symbols must never be allowed to freeze, since this might provide false and unsafe information to the pilot.

REQUIREMENT GUIDANCE (3.2.1.3.2)

A positive indication of a fault or failure condition which results in presentation of erroneous data to the pilot should be provided. The questionable data should be marked (overlaying an "X" has been used), and may be removed from the display once the pilot acknowledges it. This forces the pilot to get his information from another source, rather than use incorrect information. Some systems only remove part of the symbol, such as the alphanumerics on airspeed and altitude scales, to indicate that they are incorrect.

REQUIREMENT LESSONS LEARNED (3.2.1.3.2)

Given the requirement to remove "locked" symbols, most designs have used symbol generation schemes which inherently provide for erasure of symbols at a regular interval (should be less than one second), unless they are updated by current data.

4.2.1.3.2 Verification of symbology freeze.

__________ shall be used to determine compliance.

VERIFICATION RATIONALE (4.2.1.3.2)

Prevention of symbol freeze must be verified for safety.

VERIFICATION GUIDANCE (4.2.1.3.2)

Equipment demonstration, with input data removed or internal faults introduced, is usually appropriate to determine compliance. Since this function is usually implemented in software in new systems, it may be appropriate to audit the software to verify that appropriate steps have been taken.

VERIFICATION LESSONS LEARNED (4.2.1.3.2)

3.2.1.3.3 Symbol line width.

The symbol line width shall be __________ when measured at the 50 percent intensity points with symbol luminance set at __________ cd/m^2.

REQUIREMENT RATIONALE (3.2.1.3.3)

Symbol line width must be wide enough to make symbols easily visible, but narrow enough to produce clean-looking symbols.

REQUIREMENT GUIDANCE (3.2.1.3.3)

Line width specification of 1 mr at 3,400 cd/m^2 (1,000 fL) has been used for HUDs with good results. Another HUD required that the stroke width be between 0.12 and 0.2 times the symbol height and that stroke width be 1 $\pm$ 0.2 mr measured at the 1/e (37 percent) intensity point and at 3,400 cd/m^2 (1,000 fL) luminance (e = base of natural logarithms, or 2.72). Assuming a Gaussian spot profile, the width at 1/e is 1.2 times the width at 50 percent. Line width should be specified and measured based on the 50 percent amplitude point, since this is common practice and easiest to measure. However, this is an indirect control of line width as seen by the eye; the eye will see the line width near the 5 percent point.

The concept of "line width" is different on matrix-type displays, such as an LED array or LCD matrix, where lines have sharp edges rather than a gaussian profile. On these displays, the width of a line in pixels should be stated. Crude characters can be made with a one-pixel wide line; two-pixel wide lines allow for smaller "notches" and some fail-redundancy, since one stuck pixel or line cannot destroy the character. (See "Improved Character Readability In Spite of Pixel Failures: A Better Font", Jim Uphause et al, NAECON '90) Three-to five-pixel line widths are needed to produce smooth curves and uniform line width at all orientations. SAE ARP 4256, "Design Objectives for Liquid Crystal Displays for Part 25 (Transport) Aircraft" recommends that minimum line with be not less than 70 percent of maximum line width at any orientation.

REQUIREMENT LESSONS LEARNED

HUDs which display raster video (for night use) have had difficulty meeting a video resolution requirement (requiring a small spot size) and the minimum stroke symbol line width (which requires a larger spot size). These two requirements must be made compatible, otherwise "tricks" such as defocusing the spot in stroke mode will be required. Precisely controlling and measuring line width is difficult, and since line widths from 0.5 to 1.5 mr are visually acceptable, a wider tolerance such as 1+, -0.5 mr may be appropriate.

4.2.1.3.3 Verification of symbol line width.

Symbol line width shall be measured.

VERIFICATION RATIONALE (4.2.1.3.3)

Symbol line width must be verified to assure that symbols are clearly visible and aesthetically pleasing.

VERIFICATION GUIDANCE

The usual method of measuring line width is to electronically move the line on the HUD past the slit in a slit-aperture photometer.

VERIFICATION LESSONS LEARNED

3.2.1.3.4 Primary symbology checking.

Primary symbology consists of altitude, airspeed, pitch, roll, heading, vertical velocity, velocity vector (flight path marker), horizon line, and __________. When incoming data or processing that affects the primary symbology is identified as invalid (for example, a fail indication from a self-test), a positive indication of the failure condition shall be provided and the affected primary symbology shall be rendered unreadable and/or removed from the display. The processor shall check the information (incoming data) needed to generate the primary symbology to determine if it is reasonable with respect to the physical aircraft parameters (rate of change, maximum value, minimum value, period between change, etc.). The equipment shall also cross-check related data for predetermined difference if more than one source is available. If the incoming data is not reasonable or does not fall within the predetermined differences, then the symbology associated with the data shall __________.

REQUIREMENT RATIONALE (3.2.1.3.4)

Primary flight symbology must be checked for accuracy, since it is critical to safety.

REQUIREMENT GUIDANCE (3.2.1.3.4)

This requirement applies to any display which is designated as a primary flight instrument or is likely to be used as such. In the past, HUDs were generally not designated as primary flight instruments, but pilots tend to use the HUD symbology as if it were their primary instruments, so the accuracy of that symbology becomes critical to flight safety. The requirement to remove defective or "locked-up" symbols has been used on several HUDs. Checking for reasonable values and cross-checking between data sources has only been required in special cases.

REQUIREMENT LESSONS LEARNED (3.2.1.3.4)

Criteria for accepting an electronic display as the primary flight display have been developing slowly. For further discussion, see 4.2.1.1 and 3.2.1.3 herein and the specific requirements of MIL-STD-1787.

4.2.1.3.4 Verification of primary symbology checking.

__________ shall be used to verify that primary flight symbology is checked and presented properly.

VERIFICATION RATIONALE (4.2.1.3.4)

Symbology must be checked for safety.

VERIFICATION GUIDANCE (4.2.1.3.4)

Verification of a fault-checking system's capabilities can get very involved. The verification should include insertion of faults or incorrect data bits to demonstrate appropriate removal of symbols. If an extensive software validation is being performed, some of the functions may be verified by analysis. If the display is to be certified as a primary flight instrument, the test and validation will have to be very thorough to insure safe operation.

VERIFICATION LESSONS LEARNED (4.2.1.3.4)

3.2.1.4 Display modes.

The equipment shall provide the following modes of operation: __________.

REQUIREMENT RATIONALE (3.2.1.4)

Display modes must be specified to assure that the display performs all of its desired functions.

REQUIREMENT GUIDANCE (3.2.1.4)

Description of display modes should come out of system design and configuration studies. For example, a HUD might have a landing mode, a navigation mode, two or three weapon delivery modes, and a built in test mode. An integrated control and display unit (ICDU) might have navigation, communication, system status, and built-in-test modes.

REQUIREMENT LESSONS LEARNED (3.2.1.4)

4.2.1.4 Verification of display modes.

Operation in all display modes shall be demonstrated.

VERIFICATION RATIONALE (4.2.1.4)

Proper operation of equipment modes can be verified by a demonstration.

VERIFICATION GUIDANCE (4.2.1.4)

A demonstration can show that each of the equipment modes functions as required.

VERIFICATION LESSONS LEARNED (4.2.1.4)

A system integration lab or "hot bench" is an excellent means of evaluating whether the display modes are adequate for the mission. The KC-135 fuel savings advisory/cockpit avionics system (FSA/CAS) ICDU paging scheme and operator interface was thoroughly exercised and debugged on a hot bench throughout its development. The testing was accomplished using engineers and aircrews, and resulted in identification and correction of software design flaws early in the program.

3.2.1.5 Video resolution.

The vertical resolution shall be sufficient to produce ten percent minimum modulation when one half of the scan lines are "on" while operating in __________ raster format. The horizontal resolution shall be __________ lines per __________ minimum with a ten percent line modulation. These requirements are to be met while simultaneously meeting the contrast, luminance, and ambient requirements of 3.2.1.6.

REQUIREMENT RATIONALE (3.2.1.5)

Resolution represents the display's ability to present sharp edges and details in an image. This paragraph applies to CRT displays. For a flat panel matrix display, a statement of the number of pixels, pixel spacing, and pixel shape may be appropriate. A separate specification of line width in addition to resolution requirements on CRT displays is redundant, unless the CRT is also used for stroke-written formats (see 3.2.1.3.3). Resolution patterns are seen by the eye in a manner directly analogous to the resolution measurement.

REQUIREMENT GUIDANCE (3.2.1.5)

The raster format of the display must be compatible with the system, and will generally be one of the accepted standards (525-line, 485 active or 875-line, 809 active). The number of active raster lines is generally the limiting factor in vertical resolution. The useful vertical resolution on analog video can be obtained by multiplying the number of active raster lines by the Kell factor, which is normally accepted to be 0.7. The Kell factor accounts for the fact that raster lines represent a "sampling" of the actual analog image. The Kell factor does not apply to information which is digitally inserted on raster lines.

An ideal raster should have the vertical spot size (at 50 percent point) equal to or a little smaller than the raster line spacing, since this will produce very little vertical modulation with all the raster lines turned on, but will produce a noticeably dark line when one line is turned off. Thus the typical requirement would be to present 10 percent modulation with one half the raster lines turned on and the alternate ones turned off.

Horizontal resolution is normally specified in "lines", either per inch, per picture width, or per picture height, and should not be confused with the number of raster lines. "TV lines per picture height" are the units for CRT horizontal resolution in EIA-RS-170. Resolution is sometimes specified in line pairs per cm (or per inch). Since one "line pair" is the same as two "lines", line pairs per cm can be converted to "TV lines per picture height" by multiplying line pairs per cm by two times the picture height. Note that for a 4:3 aspect ratio display (normal rectangular TV), this means the number of lines per inch is multiplied by the (smaller) vertical screen dimension to get "TV lines per picture height".

It is common practice to specify resolution at a 10 percent contrast modulation point. This is actually just one point on the contrast transfer function (CTF) curve. The CTF curve is a plot of contrast modulation measured on the CRT versus spatial frequency (resolution). CTF is measured using a square wave input wave form. A similar measurement, modulation transfer function (MTF), uses a sine wave input. CTF and MTF can be related, using Fourier analysis, but the easiest approach is to use square waves and keep everything in terms of CTF. A typical display unit CTF curve approaches 100 percent modulation (100 x C_m, see section 5) at low spatial frequencies, then gradually rolls off at higher frequencies and passes through the 10 percent contrast modulation point at the specified resolution. An ideal CTF curve would remain high out to the frequency of the highest spatial frequency in the image and then roll off sharply to reject high frequency noise. Therefore it is best to specify several points on the CTF curve, requiring high modulation capabilities at the low and medium spatial frequencies and 10 percent modulation at the stated resolution. This is normally difficult to do because of the general lack of data on the required shape of the curve and lack of data on what curve is achievable by current displays. An alternative would be to specify resolution at lower frequencies, but require higher modulation; for example, 70 percent modulation at 400 lines rather than 10 percent modulation at 800 lines. This philosophy has never caught on in practice since it makes the stated resolution of a system a lower, less impressive number.

For highly dynamic scenes, such as might occur on a helmet mounted display, a valuable extension to CTF is the concept of dynamic CTF. It measures contrast transfer as a function of image motion (fraction of subtense moved per second) and allows one to analyze and compare smearing/blurring caused by various lags, persistences, and frame rates.

Some criteria used to establish the horizontal resolution requirement are as follows:

a) Display resolution should be better than the best sensor being used in the system to prevent the display from seriously limiting system performance. For example, for a FLIR providing resolution of 400 lines, the display should have resolution (at 10 percent modulation) 20 percent to 50 percent better than this to insure that it will provide good modulation at the frequencies contained in the FLIR video. Note that a display whose CTF is less than unity at any spatial frequency where the sensor's CTF is not zero will reduce the system CTF.

b) Display resolution must meet or exceed the criteria for number of lines per symbol height and width for symbology and alphanumerics (see symbology paragraph herein).

c) Horizontal resolution must not be specified so high as to cause gaps between raster lines (due to small spot size). Tricks, such as using a CRT spot which is elongated in the vertical axis or is "wobbled" vertically while it scans horizontally, have been devised to overcome this problem. This should only be necessary in a display which operates over a wide range of line rates. To require a horizontal resolution significantly greater than the number of active raster lines serves no practical purpose, since the resolution of most sensors is not substantially in the horizontal axis than in the vertical.

d) Horizontal resolution should not be specified much higher than the human eye's ability to resolve. Normal visual acuity ranges from about 30 to 60 cycles per degree under varying brightness and contrast conditions, but rarely exceeds 40 cycles per degree outside the laboratory conditions. This leads to a maximum useful display resolution under good viewing conditions of approximately 67 lines per cm (170 lines or 85 cycles per inch) at a normal 76 cm (30 inch) viewing distance. The useful display resolution under inflight conditions will actually be somewhat less than this due to vibration, stress, low brightness and contrast, etc. A display with high modulation at this frequency would provide the sharpest detail resolvable by the eye. Current display technologies or sensors rarely achieve this.

Examples of specified resolution on some existing equipment are as follows: (some are based on limiting resolution rather than 10 percent modulation.)

Commercial VHS VCR	280
NTSC TV	350
5-inch color CRT (.21 mm pitch shadow mask)	500
16 mm film	600
35 mm film	1300
VGA PC monitor	640 x 480 pixels
High definition TV (proposed)	1920 x 1080 pixels

REQUIREMENT LESSONS LEARNED (3.2.1.5)

4.2.1.5 Verification of video resolution.

Vertical and horizontal resolution shall be measured with a scanning photometer (may use a slit aperture), with the display adjusted to meet the luminance and contrast requirements herein, all in the presence of a __________ lm/m^2 ambient. Contrast modulation may be measured in the dark and mathematically corrected for ambient illumination effects if the results can be demonstrated to be equivalent. Contrast modulation is defined as $(L_t-L_b)/(L_t+L_b)$. The test shall be performed using a square wave video signal, and using a measurement aperture no greater than 20 percent of the display's line width.

VERIFICATION RATIONALE (4.2.1.5)

Resolution must be verified; there are numerous testing methods which can be used, and results are generally different depending on the one used, so one common, repeatable test is defined here.

VERIFICATION GUIDANCE (4.2.1.5)

On displays with discrete visible pixels, pixel density can be verified by inspection, counting the pixels with an inspection microscope. However, this does not fully characterize image sharpness. The visual sharpness and image quality on a matrix display (such as an LCD) is dependent on the line-forming algorithm (antialiasing) and spatial, temporal and chromatic noise content, in addition to the actual number of pixels resolution. The pitch-and-line width measurement approach discussed below may be used on a matrix display to assess anti-aliased line profile if the software can provide for sweeping a line across the screen in known spatial increments. In this case, a photometer is focused on a single addressable element to make the measurement. As the line is swept past the measured element, each of the gray levels of the line may be measured as a function of the line position. Note, however, that this primarily provides a means of validating the line-writing algorithm, which in turn determines the intended shape of the line's luminance profile. It does not give any indication of other image quality attributes such as spatial noise induced by the sampled reconstruction nature of the x-y matrix, nor of orientation or position dependencies of image quality (resolution, and spatial and chromatic noise).

At the specified resolution, a CRT should provide a minimum of 10 percent contrast modulation, both horizontally and vertically when measured with the scanning photometer technique. This test must be done on a bright patch of video (meeting the luminance and contrast requirements herein, under worst case lighting conditions) to be representative of display performance under these conditions. There has been no consistent application of this rule in the past, which helps to explain some of the great variation in specified resolution among displays. In some cases it may be necessary to also specify resolution in a dark ambient to satisfy everyone's desire for a large, impressive display resolution number.

It can be very difficult to measure the resolution in the specified high ambient conditions, since the photometer must normally be very close to the display and will cause shadows. Therefore, it is acceptable to measure symbols, background, and reflected ambient separately, then analytically find the modulation at high ambient.

This test is done with a photometer equipped with a small slit (typically 0.4 x 10 minutes of arc), or a very small aperture and a scanning device, which can either be part of the photometer or a translating table. The photometer data will then produce a plot of luminance versus position on the screen. Contrast modulation (C_m) is defined in section 5. The input signal is assumed to be 100 percent modulated, i.e., the white level is the "peak video voltage" the display specification or interface calls for and the black level is the specified black level, so there is no need to divide by the input modulation when calculating the contrast transfer function.

This test tends to be difficult and time-consuming; visual inspection of a resolution test pattern may be used in production acceptance tests if the specified requirement is consistently met (as verified with the scanning photometer).

Accurate, repeatable resolution tests for patterned-screen CRTs (shadow mask or beam index) are not in general use. While the scanning slit test might be useful at low resolutions on these CRTs, airborne color CRTs are often designed to approach the resolution limit of the color pattern. In this case the CTF data would be good at low frequencies, but would show extreme fluctuations at resolutions near the color pattern pitch. A practical work-around to this has been to specify size of the color pattern (typically 0.3 or 0.2 mm triad pitch for high resolution shadow mask CRTs) and the line width. The line width must then be measured, generally by slowly sweeping a line across the screen and measuring its profile with a photometer (See TEP 105-9, -Line Profile Measurements in Shadow Mask and Other Structured Screen Cathode Ray Tubes".) The photometer must have a small enough aperture to be focused on one phosphor dot and exclude light from other dots.

SAE ARP-1782 provides additional guidance on resolution testing techniques for CRTs.

VERIFICATION LESSONS LEARNED (4.2.1.5)

Measurement of resolution on video which is bright enough to also meet the luminance and contrast requirements is a severe test for a CRT, especially in a full sunshine environment (see 3.2.1.6).

3.2.1.6 Display luminance, contrast, and viewing angle.

The luminance, contrast, and viewing angle requirements of the following subparagraphs shall be met when measured from the design eye position. The display luminance and contrast shall not change more than ± __________ percent when changing modes. No random bright flashes shall occur during mode switching.

REQUIREMENT RATIONALE (3.2.1.6)

Display viewability with appropriate head motion and mode switching is essential to display usefulness.

REQUIREMENT GUIDANCE (3.2.1.6)

Luminance change associated with mode changes should not exceed 40 percent. For some instruments and displays, it has been required that all information remain readable at any viewing angle up to 30 degrees with respect to a line normal to the display for a complete 360 degrees revolution around the normal line. (See 3.2.1.6.7, Viewing Angle.)

REQUIREMENT LESSONS LEARNED (3.2.1.6)

4.2.1.6 Verification of display luminance and contrast.

Display luminance and contrast shall be measured by ___________.

VERIFICATION RATIONALE (4.2.1.6)

Luminance and contrast must be measured to assure display usefulness.

VERIFICATION GUIDANCE (4.2.1.6)

A spot photometer should be used to measure luminance of the various shades of gray, from each of the eye positions defined. Contrast can then be calculated, using the definition in section 5. Chromaticity measurements must be taken with a spectroradiometer.

VERIFICATION LESSONS LEARNED (4.2.1.6)

Two major causes have been identified for errors in luminance measurements on test units exhibiting highly saturated color or short spikes of light output (e.g., CRTs with P-43 or P-53 green phosphor).

The first relates to the spectral properties of the light source. The accuracy of a spot photometer can be degraded by as much as 30 percent (potentially more) if the photopic response of the photometer's filter/photo multiplier tube combination deviates significantly from the ideal CIE Y luminosity function. This problem is most evident for strongly colored light sources, particularly for blue and red primary colors. Luminance correction factors can be generated from the spectral energy distribution of the colored source and the spectral response of the photometer, as follows:

$$\text{Factor} = \frac{\text{CIE Y luminosity function)} \cdot \text{(Spectral energy distribution of colored source)}}{\text{(Photometer spectral response)} \cdot \text{(Spectral energy distribution of colored source)}}$$

One-nm wavelength increments are needed for sources exhibiting narrow emission bands, while larger wavelength increments (i.e., 5 nm) may suffice for broader band sources (e.g., incandescent). The CIE Y luminosity function ("photopic curve") can be obtained from a photometer manual. The spectral energy distribution of the colored source must be measured on a similar sample using a spectro radiometer. The photometer spectral response can be obtained from the photometer manufacturer.

The second luminance measurement problem arises from the inability of a photometer to respond dynamically to bright, concentrated, light sources such as the moving spot of a CRT. This problem has been observed with monochrome (GY, or P-43) CRTs at luminance greater than 686 cd/m^2 (200 fL). It is possible for a very high momentary peak brightness to cause the photometer electronics to saturate, clipping the signal. All photometers respond differently, but all photometers will read erroneously low in this circumstance. Some photometers give a warning of such an over-range condition.

Most photometers are equipped with neutral density (ND) filters. When measuring CRTs, it is recommended that the highest attenuation filter be used which will still give the needed number of significant digits in the luminance result. This will help ensure that the peak luminance is within the dynamic range of the photometer. However, in some cases (e.g., high luminance CRT displays) the maximum available attenuation may not be sufficient for accurate luminance measurements. For example, an F-117 display produced such an over-range with an ND-4 (four orders of magnitude attenuation). An accurate measurement of luminance could only be obtained with an additional attenuation of ND-2 (total attenuation of ND-6).

3.2.1.6.1 HUD stroke-written line luminance.

The luminance of all stroke-written symbols shall be such that projected images are clearly defined when superimposed on a background luminance of 34,000 cd/m^2 (10,000 fL) and color temperature of 3,000 to 5,000 Kelvin. The average line luminance over the total symbol area shall be a minimum of ___________ cd/m^2 with a design goal of ___________ cd/m^2 when viewed through the HUD combiner glass. The contrast ($[L_t - L_b]/L_b$) of the symbology with a 34,000 cd/m^2 ambient background shall be a minimum of ___________ with a design goal of 0.5. Luminance shall not degrade more than ___________ percent when measured from anywhere within ___________ cm of the design eye position.

REQUIREMENT RATIONALE (3.2.1.6.1)

HUD brightness is critical for performance in sunshine.

REQUIREMENT GUIDANCE (3.2.1.6.1)

This requirement applies only to HUDs. Line luminance of 5440 cd/m^2 (1,600 fL) and contrast of 0.2 (contrast ratio of 1.2:1) is quite feasible and provides symbols viewable in full sunshine. Design goals of 17,000 cd/m^2 (5,000 fL) and contrast of 0.5 would provide more comfortable viewing in very bright conditions. Note that this is a lower contrast than is recommended for head down displays, but is adequate for a HUD because a HUD is much brighter, there is color contrast between green HUD symbols and the background, and large, single-shade graphics are used.

There is normally no need to specify contrast in the dark on a CRT-based HUD, since the CRT can easily achieve contrast of over 100 in the dark. If other display technology is used (such as LCDs) that do not have a very black background, there will be "background glow" projected onto the outside scene, which is very difficult to see through. This can also be a problem on panel (head down) displays, where the "background glow" amounts to stray light being emitted into the cockpit, where it will cause reflections in the canopy/windshields.

Note that the ambient for a HUD is specified in units of luminance (cd/m^2 or fL) of the background rather than the illuminance units used for panel displays. This is because the imagery is projected onto the outside world, and is seen relative to the brightness of that outside scene, not the illumination level in the cockpit.

Head motion requirements are important where diffraction optics and/or directional filters are used, since there is generally a loss of on-axis luminance performance as the exit pupil is made larger (allowable eye motion increased). 25 percent maximum luminance degradation within 2 cm of the design eye position has been specified for a HUD; this appears to be a bare minimum.

REQUIREMENT LESSONS LEARNED (3.2.1.6.1)

Symbol brightness is achieved at the cost of other parameters such as CRT life and combiner see-through clarity. Tests have shown that there is a definite reduction in CRT life expectancy when operated at very high luminances. It is important to verify that this reduction in CRT life can be tolerated.

4.2.1.6.1 Verification of HUD stroke-written line luminance.

The requirements of 4.2.1.6 apply.

3.2.1.6.2 HUD raster luminance.

The raster video luminance shall be such that __________ shades of gray (__________ steps, __________ levels) are visible against a __________ cd/m^2 background luminance with an equivalent color temperature of 3,000 to 5,000 Kelvin. The contrast ($[L_t-L_b]/L_b$) of the peak raster video with a __________ cd/m^2 ambient background shall be a minimum of __________. The ratio between adjacent gray shades shall be a minimum of 1.4:1 (contrast of 0.4).

REQUIREMENT RATIONALE (3.2.1.6.2)

This requirement is needed (on HUDs with video) to assure that HUD video is visible against appropriate background brightness.

REQUIREMENT GUIDANCE (3.2.1.6.2)

Visibility of six shades of gray against a 170 cd/m^2 (50 fL) background with a contrast of 7.0 has been demonstrated. This is not bright enough for viewability in full sunshine but may be usable against dark backgrounds like dirt or trees in daylight. Note that the number of steps is one less than the number of levels or shades.

REQUIREMENT LESSONS LEARNED (3.2.1.6.2)

There may be systems that would benefit from a full sunshine HUD video capability, but current technology makes this difficult to achieve in a practical design.

4.2.1.6.2 Verification of HUD raster luminance.

The requirements of 4.2.1.6 apply.

3.2.1.6.3 MFD luminance and contrast.

The luminance and contrast of all displayed data shall be adequate for easy visibility in illumination environments from __________ to __________. The following contrast requirements shall be met in a combined environment consisting of __________ lux (__________ fc) diffuse illumination and the specularly reflected image of a __________ cd/m^2 (__________-fL) glare source. The contrast ($[L_t-L_b]/L_b$) of stroke-written symbols shall be __________ minimum. The display shall be capable of presenting a minimum of __________ shades of gray (__________-1 steps) and the overall contrast of raster video (between brightest and darkest shade) shall be __________ minimum. The ratio between adjacent gray shades shall be a minimum of 1.4:1 (contrast of 0.4). The difference luminance (ΔL) between the brightest image and the dimmest in this environment shall be at least __________ cd/m^2 (__________ fL). The minimum contrast and shades of gray requirements above shall also be met in any less bright environment. The contrast between an "off" element and its background shall be less than __________.

REQUIREMENT RATIONALE (3.2.1.6.3)

This requirement is needed to assure that stroke-written symbols and/or raster video on head down displays is visible in appropriate lighting environments. It includes a dual (diffuse and specular) lighting environment to simulate lighting in the real world and avoid some of the disparity which has existed between test results and real experience. The illumination and glare source luminance of the worst case environment for the display technology being used and the appropriate aircraft types should be filled in, as discussed below. The difference luminance capability of the display is specified in order to limit the shift in luminance which an operator experiences when shifting his gaze from the surroundings to the display and also to overcome veiling glare which occurs when high luminance levels (e.g., white clouds, sun, etc.) are in the operator's field of view.

REQUIREMENT GUIDANCE (3.2.1.6.3)

This requirement should be applied to all head-down or panel displays. It addresses only luminance contrast; evaluation of color difference on multicolor displays should be based on the "color difference" paragraph herein. The first sentence should be filled in with a generic description of the lighting environment, for example, "full sunshine to full darkness" for a fighter cockpit.

The combined diffuse and specular environment described herein is finding increased use, and is also specified in ASC/ENFC 96-01 and SAE ARP-1782. The use of diffuse-only tests in the past appears to account for some of the variation in test results for different devices and general disagreement on what contrast values are acceptable. Since both the specular component and the diffuse component affect readability, testing to one or the other is inadequate. Note that a diffuse ambient illumination level falling on a display should always be specified in units of illumination (lux, lm/m^2, or fc) while light radiating from a surface, such as the face of a CRT or a reflective surface should be in luminance units (nits, cd/m^2, or fL).

The following table contains suggested values for illumination and glare source luminance based on measurements taken in several aircraft cockpits. Note that the traditional fighter cockpit environment specification of 108,000 lux (10,000 fc) diffuse illumination has a 6,800 cd/m^2 (2,000 fL) glare source added to it. The glare source represents objects such as the pilot's helmet or flight suit, illuminated by sunshine, being reflected in the display. Much brighter glare sources are possible, especially if the display is not optimally positioned in the cockpit. For example, if the face of a display is positioned at such an angle that, from the design eye point, the "angle of incidence = angle of reflectance" rule allows the pilot to see reflections of the sky, the glare source could be a white cloud at 34,000 cd/m^2 (10,000 fL) or even the sun itself (several million fL).

An 86,400-lux (8,000-fc) diffuse illumination level may be adequate for instrument panel displays in some fighters. This is based on actual cockpit measurements in a T-38 and an F-16, which showed that the high illumination levels outside the cockpit are generally attenuated to less than this by passing through the canopy and hitting the instrument panel at oblique angles.

In the past, separate specification requirements for anti-reflection coatings on CRT faces prevented excessive specular reflections. This provided adequate results in many cases, but the desire in this document is to state the performance required (in terms of contrast in the presence of a glare source) without describing a specific design or presenting a solution that might only apply to CRTs; it is actually the inner surfaces, rather than the front surface, that contribute most of the specular reflections on an LCD.

TABLE I. Suggested requirements for illumination and glare source luminance.

	Sunshine ambient				
	Bubble canopy	Cockpit with roof	Shaded	Indoor enclosed cabin	Dark
Diffuse illumination	108,000 lux (10,000 fc)	86,000 lux (8000 fc)	3240 lux (300 fc)	540 lux (50 fc)	0
Glare source	6800 cd/m^2 (2000 fL)	6800 cd/m^2 (2000 fL)	6800 cd/m^2 (2000 fL)	3400 cd/m^2 (1000 fL)	0

NOTES to Table I:

1/ The bubble canopy (fighter cockpit) environment assumes a bubble canopy and good display placement (i.e., no specular reflection of the sky). Where specular reflections of the sky are a problem, such as on console-mounted lighted legend switches, the glare source should be increased to 34,000 cd/m^2 (10,000 fL).

2/ The cockpit with roof (transport) environment assumes an opaque roof overhead, such that direct sun can only hit the display a small percentage of the time and only at large angles off axis.

3/ The "shaded" environment actually occurs most of the time for displays in an instrument panel under a glare shield. (See "Multifunction Displays optimized for viewability", R. Hockenbrock and J. Murch, SPIE vol. 1117, Display system optics II (1989).) The low diffuse ambient makes it impossible for a display without high light output or high reflectance to have the high delta luminance needed for good legibility in this environment. The "10,000 fc" environment has been used by itself as a legibility criteria, leading to displays that are optimized for that rare case but not designed for good legibility in the normal (shaded) environment. It may be more appropriate to require high luminance and contrast capability in the "shaded" environment and only require minimal performance in the sunshine environment.

4/ The enclosed cabin environment is like an office: the glare sources are ceiling lights and small windows.

5/ Sunshine at noon at high altitude can reach 154,440 lux (14,300 fc) or more. This table assumes the display is inside a canopy (typically less than 85 percent transmission) and the sun cannot hit the display within about 30 degrees of perpendicular.

Table II provides suggested contrast requirements based on a variety of human factors tests and practical experience with existing aircraft displays. They represent the monochrome contrast needed to assure rapid, accurate reading of the information in a wide variety of lighting, stress, and vibration environments-i.e., a fully legible display. Information with lower contrast may still be visible and readable but will look washed out in some situations and may not provide the reading speed and accuracy required.

TABLE II. Suggested contrast requirements.

	Required contrast	Goal contrast	Contrast compensations for other character h and SW
Numbers only	$\geq$ 1.5 for h = 5.0 mm and 0.12h $\leq$ SW $\leq$ 0.2h	2-20	Multiply required contrast by 5.0/h for 2.5 $\leq$ h $\leq$ 7.5 mm and by 0.12h/SW for 0.01h $\leq$SW $\leq$0.12h
Alphanumerics	$\geq$ 2.0 for h = 5.0 mm and 0.12h $\leq$ SW $\leq$0.2h	3-20	
Graphics and alphanumerics	$\geq$ 3.0	3-20	
Video	$\geq$ 4.66	20-50	

NOTES to Table II:

1/ h is character height, SW is character stroke width. Character height should never be less than 2.5 mm. This table assumes a 76-cm viewing distance.

2/ The 4.66 overall contrast for video represents six levels of gray (five steps), each a minimum of sq rt of 2 (approx. 1.41) times the next. At least eight 1.41:1 levels should be visible under other than worst-case illumination environments. This requirement has been applied to CRTs, with the understanding that a CRT is an analog device and it can actually produce an infinite number of levels between the ones specified. Systems which quantize the luminance levels must be able to produce a greater number of smaller levels (e.g., 64 levels of each primary color), assuming the goal is to display video without objectionable contouring.

3/ These minimums have been used in CRT display specifications when being tested in the high brightness environment, with the assumption that contrast will improve from the “minimum” to the “goal” range when in a less bright environment; this assumption may not be valid for a reflective device, such as a reflective LCD or painted instrument. The worst-case environment for the particular display technology should be substituted.

4/ The minimum required contrast for video has been met with monochrome CRTs in sunshine, but typically cannot be met with color CRTs. Color Active Matrix LCDs can achieve contrast of over 6 in this combined environment.

5/ For a display device where unlighted characters shouldn’t be noticeable, the contrast between unlighted segments and the background (C_{ul}) should not exceed 0.1. C_{ul} of up to 0.25 may be acceptable where visible segments are not objectionable.

6/ On hybrid (stroke and raster combined) CRTs, stroke-written symbols are normally brighter and higher contrast than raster symbols and video, due to inherent characteristics of CRTs. They are generally specified as having a higher contrast ratio (relative to black) than the video, with the understanding that they will be written over the video and may only achieve the minimum contrast there.

7/ When raster symbols are written over video, they must be a level of gray brighter then the video; otherwise it is difficult to achieve adequate contrast between the symbol and bright video. Enhancement techniques, such as blocking out surrounding video or shadowing (blocking out one pixel all around the symbol), may be required.

8/ High display luminance (ΔL) is required to minimize the time required for the eyes to adapt from high exterior luminance (tops of clouds or fresh snow in sunshine) to the lower luminance of the displays, and to overcome veiling glare (when flying toward the sun).

9/ Electromechanical instruments were often specified to have a contrast of 4.0 in a 10,000 fc diffuse environment. Their contrast would be significantly less than this in a combined environment including a specular component because of the specular reflection of the cover glass and the painted instrument face itself. Critically important items, such as the needle on an altimeter, were typically made larger to improve legibility.

It is desirable to limit the shift in luminance to about 20:1 when the operator looks from the display to a 34,000 cd/m^2 (10,000 fL) cloud and back. So far it has been possible to achieve about 50:1. To get a 50:1 value, specify a difference luminance (ΔL) of 680 cd/m^2 (200 fL) between the display highlights and the display background at the brightest setting. When a display is located low in the cockpit, where the outside scene is not in the eye's instantaneous field of view at the same time as the display, the problem of veiling glare becomes less severe, and this number can be decreased to 340 cd/m^2 (100 fL). In an office or enclosed cabin environment, luminance difference of 35 cd/m^2 (10 fL) is adequate, although most users prefer higher luminance (170 cd/m^2 or 50 fL).

As with most other performance requirements, improvements in luminance and contrast can often be achieved only at the cost of other parameters (cost, reliability, resolution, power dissipation, etc.) in an equipment design, so tailoring the requirement based on critically of the information being displayed and capability of the display technology available may be appropriate.

REQUIREMENT LESSONS LEARNED

The need for high luminance output (difference luminance) in displays used by an operator exposed to sunshine (even if the display is in a shadow) has not been widely recognized in specifications. This can be a real problem for devices that have adequate contrast ratio but do not emit or reflect enough light to minimize time required for eye adaptation and overcome veiling glare.

4.2.1.6.3 Verification of luminance and contrast.

Display luminance and contrast shall be measured using the test setup shown in figure 1 and using the diffuse illumination and specular glare source luminance specified in section 3 herein. Light sources used shall have a color temperature between 3,000 and 5,000 Kelvins. The following measurements shall be taken and used to calculate the required contrast ($[L_t - L_b]/L_b$):

L_t, the total luminance of the image, or brighter area, including any background or reflected light.

L_b, the luminance of the background, or dimmer area, measured in the specified lighting conditions, including any reflected light and any stray display emissions.

ΔL, (delta luminance, or difference luminance) the difference between the higher luminance (L_t) and the lower luminance (L_b).

Measurements shall be taken with a photometer having a sensing aperture equivalent to at least 1.8 minutes of arc, as measured from the normal operator viewing distance. If luminances of smaller areas are measured, then a series of measurements shall be taken within an area equivalent to the 1.8 minute of arc area and the luminance of the active areas shall be averaged with the luminance of any inactive areas on an area-weighted basis.

On large displays, such as a CRT, measurements shall be taken at five positions distributed over 80 percent of the screen area and averaged.

If the dimensions of the image elements are large enough to permit several non overlapping measurements to be made within the image element boundaries, multiple luminance readings shall be taken and averaged to establish the average element luminance.

If it can be demonstrated that ΔL does not change under varying lighting conditions, L_t can be calculated by measuring ΔL and L_b and adding them. If it can be demonstrated that equivalent results can be obtained by measuring in lower ambients (e.g., 54,000 lux rather than 108,000 lux), then scaling up the results, then the test may be done in the lower ambient.

VERIFICATION RATIONALE (4.2.1.6.3)

Contrast and luminance must be verified to assure good legibility. A specific test technique is described in an attempt to make the test results repeatable and consistent. This procedure is intended to give a good representation of real world lighting conditions without requiring the use of expensive or exotic equipment. A similar procedure is required by SAE ARP-1782 and by ASC/ENFC 96-01.

VERIFICATION GUIDANCE (4.2.1.6.3)

This paragraph should be used intact whenever specific display unit luminance, contrast, and combined environment requirements are imposed in section 3 of the specification.

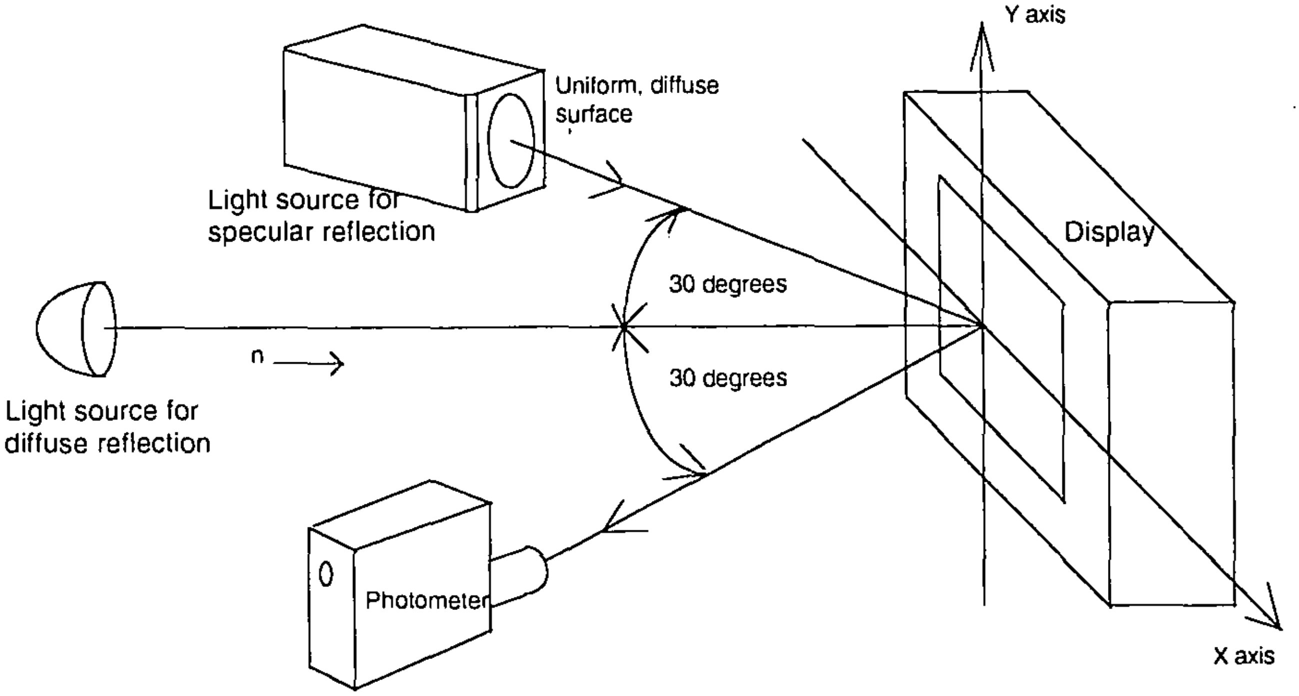

FIGURE 1. Combined specular and diffuse measurement setup.

NOTES to Figure 1:

1. Luminance of the glare source is measured by putting a mirror (preferably front-silvered) in place of the display and leaving the photometer focused at the display surface.

2. The diffuse ambient should be measured by substituting a diffuse surface of known reflectance for the display surface and measuring its luminance, then calculating the illumination level.

3. The diffuse and specular reflected light can be measured separately and summed or measurements can be taken directly with both light sources on at once.

4. Ordinary photo studio flood lights are not purely diffuse light sources, but are an acceptable approximation in this test.

5. Contrast shall not degrade more than 20 percent from specified values when measured at angles smaller than the 30 degrees shown in figure 1, or when the diffuse reflected luminance is measured with the photometer and light source interchanged (that is, photometer on the axis of the display).

6. Contrast may be measured at angles less than the 30 shown in figure 1 if the display will always be used at these smaller angles (15 degrees is specified in some LCD standards). If an "on axis" contrast is specified along with a combined diffuse and specular ambient, the specular reflectance must be measured slightly off-axis and used (with the on-axis, in-the-dark luminance data) to calculate effective contrast in the specified ambient.

The test setup shown in figure 1 is designed to simulate a typical display installation. The photometer is near the display operator's normal viewing position, representing the operator's eye. The diffuse light source represents the sun and/or bright clouds illuminating the crewstation. The glare source represents objects in the crewstation, such as the operator's helmet or flight suit, (or, in some cases, the sky) which can be reflected directly back to the operator's eye.

The color temperature requirement on the light sources requires that the light be approximately white. Normal incandescent photo studio lights are the easiest to obtain and some of them meet this requirement. Fluorescent or arc lamps should not be used without careful analysis, since some of them radiate most of their light at one wavelength, which may or may not be close to the color of the "notch" filter used on many displays, and can therefore produce erroneous results.

Measurement of L_t and L_b is all that is necessary to calculate the contrast (as defined in paragraph 6.2 herein). ΔL is commonly measured and discussed in connection with displays, (it may be called by several other names) since it is simply the light being generated by the display, which doesn't change with different ambients on some technologies (CRTs). This quantity cannot be measured directly on a reflective-type display (for example, a passive LCD or painted instrument face), since the contrast on these displays is at least partially produced by selectively reflecting the ambient light. For CRTs, it is generally easier and more accurate to measure ΔL (with the lights turned off) and calculate L_t by adding this to L_b.

The photometer should measure an area at least as large as the area that the human eye normally averages over. Many spot photometers include a 2-minute-of-arc (1/30 degree) measurement setting which meets this requirement when the photometer is positioned at the normal viewing distance. This is important in any case where the surface being measured is not continuous. For example, the luminance inside the phosphor dots of a shadow mask CRT is much higher than the area-averaged luminance seen by a person (or a photometer with a 2-minute-of-arc measuring aperture).

Where character segments are being measured, non-uniformity within a segment can cause inconsistent measurements. In this case, several measurements should be taken and averaged to obtain an average reading.

The notes under figure 1 describe how the combined ambient lighting should be measured. While these techniques may not be as technically precise as putting the photometer in place of the display and taking measurements, they will be much easier and generally just as accurate in practice because they eliminate the need to move any of the test setup except the display. A typical test jig might provide a display support with rollers/tracks under it so the display can be slid back to permit the mirror and diffuse reflector to be accurately positioned in its place. Distances and angles in this test setup are not critical.

An ordinary photo studio floodlight is not really a diffuse light source, but in this test setup, with small off-axis angles, it is a reasonable approximation, and is probably more realistic because it more closely simulates direct sunshine mixed with diffuse light from clouds and sky. A diffuse illuminating sphere may also be used if it is modified to allow independent adjustment of the specular and diffuse reflections. With a normal diffuse illuminating sphere, when the photometer is positioned on-axis, it sees a specular reflection of its own lens, and when it is positioned off-axis, it sees a specular reflection of the internal surface of the sphere.

VERIFICATION LESSONS LEARNED (4.2.1.6.3)

Numerous different (and often contradictory) measurement techniques have been used in attempts to specify and measure contrast. It has always been difficult to compare results for different display technologies, not only because of the different terminology and techniques, but because of the different display media. For example, contrast requirements for avionics CRTs are always specified in a high ambient, since this is the most difficult environment for them and they actually achieve much better contrast most of the time, in less severe environments. A person not realizing this might wonder why an LCD having the same specified contrast looks more "washed out" in normal room light.

3.2.1.6.4 Dimming range.

The equipment shall be dimmable to a level of __________ cd/m^2 (peak brightness) in a dark ambient.

REQUIREMENT RATIONALE (3.2.1.6.4)

Night brightness must be specified to assure that an appropriately dim display is available for night missions.

REQUIREMENT GUIDANCE (3.2.1.6.4)

This requirement applies to displays which are used in an environment where the eyes must be at least partially dark-adapted and/or where the display must not create excessive light which can cause canopy reflections at night. (Also see 3.2.1.21.)

In some displays, this is a separate mode activated by a "day/night" or "day/auto/night" switch, which changes the range of brightness and contrast controls.

A dimming range was not generally specified on head-down CRT displays, since adequate range was available as long as suitable controls were provided. Adequate range may be difficult to achieve on other technology displays. Dimming to 0.34 cd/m^2 (0.1 fL) has been used, but it is still too bright to allow fully dark-adapted vision of the outside scene. Measured data indicates that some pilots use electromechanical instruments at settings as low as 0.01 cd/m^2 (0.003 fL). Some existing flat panel displays are specified at 0.034 or 0.102 cd/m^2 (0.01 or 0.03 fL). While this is too dim to make use of the eye's full resolution capability, it allows the display to still provide critical information when turned down to a level that does not produce serious canopy reflections.

The following specific requirements have been used for a HUD for a night mission: "The HUD shall be capable of providing a very dim, easily controllable image, free of background 'glow' in areas not displaying information in the night brightness mode. This mode shall allow the pilot to adjust the HUD such that symbology on the HUD, while being clearly and uniformly displayed, does not obscure outside vision of a dimly lit scene such as a horizon lighted only by moonlight. If this requirement cannot be met by accurately controlling the drive to the display in the night brightness mode, an optical filter shall be used which is automatically inserted in the optical train in the night brightness mode. This requirement will be considered to be met when the following is achieved: In a dark ambient (less than 0.107 lux) with symbols and peak white video adjusted to 1.7 $\pm$ 0.35 cd/m^2, a minimum of six shades of gray ((1.4 $\pm$0.2):1 ratio) shall be visible and the areas of the raster which are blank shall be less than 0.07 cd/m^2."

REQUIREMENT LESSONS LEARNED (3.2.1.6.4)

In the F-16, "blank" formats were made available on the MFDs to allow the pilot to eliminate canopy reflections when the MFDs were not in use. A data entry display that produced 0.34 cd/m^2 (0.1 fL) was declared "too bright" by pilots and was changed to 0.034 cd/m^2 (0.01 fL).

Some older CRT-based HUDs had a "background glow" problem at night because the CRT was not properly blanked in areas not presenting symbols. The image source in a HUD or HMD must have a very high contrast to prevent this problem.

Special color tracking circuitry was required on some color CRTs because the three color guns did not all dim together at very low settings. An alternative approach, used on some commercial Electronic Flight instruments, is to electrically limit how far the CRT can be dimmed, thus avoiding operation in the most non-linear part of its range.

4.2.1.6.4 Verification of dimming range.

The requirements of 4.2.1.6 apply.

3.2.1.6.5 Chromaticity difference.

The chromaticity difference (CD) between __________ and __________ shall be adequate for easy discrimination of __________ and be a minimum of __________ units on the 1976 CIE diagram defined in CIE Publication 15 Supplement 2 (1978), under lighting conditions of __________.

REQUIREMENT RATIONALE (3.2.1.6.5)

For color displays, simple contrast is not adequate to specify color differences. Work performed by Silverstein, Merrifield, and their colleagues for air transport displays has addressed color display luminance and contrast requirements in the avionics environment. Those data show that the introduction of color contrast greatly alters the luminance and contrast parameters as compared to monochromatic displays.

REQUIREMENT GUIDANCE (3.2.1.6.5)

For color displays, chromaticity differences (CD) can be used to quantify the discriminability of various colors. While many color difference measures have been proposed, distance between the two colors on the 1976 CIE UCS diagram is the easiest to use and seems to be a reasonable approximation to human perception of difference. Chromaticity difference (ignoring luminance difference) should be calculated as a simple vector (Euclidean) distance, like this: $CD=(\Delta u'^2+\Delta v'^2)$. The u' and v' values should be measured in the presence of the worst ambient in which the display is expected to achieve full performance.

A system of color difference equations, the CIE $L^*u^*v^*$ color space (abbreviated CIELUV) is defined in CIE publication 15 supplement 2. It is designed around the use of a reference light source shining on a reflective surface, and is therefore not clearly defined for an emissive display such as a CRT. (See "U.S. Air Force Color Display Issues", by David L. Post, S.A.E. paper 0148-7191/86/1013-1695). It has only recently come into use. There is still a great deal of uncertainty as to what values of ΔE^* are adequate under various conditions, as well as uncertainty as to how well it correlates with human perception in various parts of the color gamut.

The CIE LUV equations of CIE Publication 15 Supplement 2 (1978) are repeated here for information:

$$L^* = 116\,(Y/Y_n)^{1/3}-16 \quad Y/Y_n \text{ greater than } 0.01$$

$$u^* = 13L^*\,(u' - u'_n)$$

$$v^* = 13L^*\,(v' - v'_n)$$

$$\Delta E^* = [(\Delta L^*)^2 + (\Delta u^*)^2 + (\Delta v^*)^2\,]^{1/2}$$

Y is the luminance of the color sample and Yn is the luminance of a reference stimulus. u' and v' are chromaticity coordinates of the sample in the 1976 UCS system, u'_n and v'_n are chromaticity coordinates of a reference stimulus. These definitions assume the sample is being compared against a reference stimulus, such as CIE standard illuminant D-65.

Another measure of color capability is "color area", defined as the area within the triangle formed by the three primary colors plotted in CIE 1976 u' v' chromaticity coordinates. For example, a typical color CRT (in a dark ambient) has a color area of about 0.045 u' v' square units.

REQUIREMENT LESSONS LEARNED (3.2.1.6.5)

Color differences have not been specified in existing systems, as mentioned in the "display color" paragraph herein. It is not clear what values should be used in the blanks above.

4.2.1.6.5 Verification of chromaticity difference.

The requirements of 4.2.1.6 apply.

3.2.1.6.6 Luminance uniformity.

[a] Symbol uniformity. The difference in luminance between any symbol or symbol segment and the average within any circle whose diameter is one-fourth the display's minimum dimension shall not exceed __________ percent of the average value. Total variation across the display shall not exceed __________.

[b] Large area uniformity. The difference in luminance between any point and the average within any circle whose diameter is one-fourth the display's minimum dimension shall not exceed __________ percent of the average value when a flat field signal is applied. Total variation across the display shall not exceed __________ percent.

[c] Small area uniformity. The difference in luminance between any point and the average within any 10 mm diameter circle shall not exceed __________ percent of the average value when a flat field signal is applied. Luminance measurements shall be based on an approximately 1 mm diameter measurement area.

REQUIREMENT RATIONALE (3.2.1.6.6)

Symbols and video must appear uniform for aesthetic reasons and to avoid "dropout" of portions of symbols.

REQUIREMENT GUIDANCE (3.2.1.6.6)

Large area uniformity of ± 20 percent within one-fourth of the display and ± 40 percent overall has been required for CRT displays. Tighter tolerances are usually not necessary since the eye is not very sensitive to brightness variations over large areas. Abrupt changes (discontinuities or edges), however, are objectionable. A much tighter requirement (± 10 percent within 10 mm has been used) is needed for small area uniformity, as well as between adjacent pixels or segments in a display made up of discrete elements, especially if the non-uniformities form patterns, such as rows or columns. (See 3.2.1.6.8, Blemishes.) Uniformity must be checked at high and low brightness to assure uniform controllability at low levels.

There are several uniformity definitions, and they are routinely interchanged.
For example, with Max = 100 and Min = 80:

1)	Max / Min =	1.25 (ARP 1782)
2)	[(2*Max) / (Max + Min)] - 1 =	11 percent (ARP 1782)
3)	(Max - Min) / (Max + Min) =	± 11 percent relative to the avg.
4)	(Max - Min) / Max =	20 percent relative to max
5)	(Max - Min) / Min =	25 percent relative to min

Definition #3 ("difference over the sum") is recommended because:

a) It gives the smallest numbers - Large deviations are acceptable, but large numbers scare people, and put the manufacturer at an unfair disadvantage against competitors who use the small numbers.

b) It is a simpler equation to remember, but gives the same numbers as the equation in SAE ARP 1782.

Display uniformity numbers are meaningless unless you know how far apart the measurements were taken, hence the statement in each requirement about how much of the display the percentage applies to.

Luminance uniformity (or non-uniformity) is critical to making a display look good aesthetically, but it is not clear that it has much effect on actual user performance.

REQUIREMENT LESSONS LEARNED (3.2.1.6.6)

Some systems have non-uniformity of ± 50 percent (3:1), or even more, between the center and the edges, and this is not objectionable if it is a uniform brightness falloff over a large area. Luminance uniformity is probably the most often misunderstood and over specified parameter in display systems, mainly because of the drastic difference in visibility of small area non uniformities compared to large area non uniformities.

4.2.1.6.6 Verification of luminance uniformity.

Display luminance test data shall be used to determine compliance.

VERIFICATION RATIONALE (4.2.1.6.6)

Uniformity must be verified to assure that the display is usable.

VERIFICATION GUIDANCE (4.2.1.6.6)

Verification should be based on luminance measurements.

VERIFICATION LESSONS LEARNED (4.2.1.6.6)

3.2.1.6.7 Viewing angle.

Viewing angle shall be at least +__________ degrees up, -__________ degrees down, __________ degrees left, and __________ degrees right, relative to the central (perpendicular to the face) axis of the display. Criteria for "viewing" are:

[a] _____

[b] _____

[c] _____

REQUIREMENT RATIONALE (3.2.1.6.7)

Displays with thick bezels or protruding controls may block the view of the operator. Certain display technologies, including LCDs and any display using pupil-forming optics or a directional filter, may have narrow viewing angles.

REQUIREMENT GUIDANCE (3.2.1.6.7)

Required angles depend on the geometry of the planned installation (and any other potential installations) taking into account the need to see the far edge of the display. For example, a display on the centerline of a single seat aircraft can have narrow viewing angles (less than 20 degrees). A side-by-side cockpit may require at least some readability from across the cockpit, which may exceed 45 degrees (depending on viewing distance and width of cockpit). Possible criteria include:

a) No display face blockage by bezel or controls.

b) No critical information blocked by bezel or controls.

c) No contrast reversal or color reversal

d) Contrast does not degrade to less than 70 percent of the value on axis.

e) Contrast does not degrade to less than 3.0.

f) No visible change in color or loss of contrast.

g) Information remains readable.

The criteria chosen (more than one may be needed) depends on the criticality of the information.

Stating angles as up, down, left, and right allows for asymmetrical situations (which are common) and eliminates the confusion over total viewing angle vs. angle from normal. The reference axis from which angles are measured must also be specified - in some cases the perpendicular axis is used and in others a standard viewing position is defined.

REQUIREMENT LESSONS LEARNED (3.2.1.6.7)

LCDs have had difficulty achieving wide viewing angles, especially when driven with shades of gray (video); any viewing angle characteristics specified should be evaluated in a cockpit mockup to verify they are adequate, but not excessive. Devices which reflect or radiate light from a diffuse surface or gas (painted instruments, CRTs, plasma displays) generally have very wide viewing angles, limited only by bezel blockage, curvature of the display face, or off-axis reflections in the cover glass.

Where LCDs are used for display of video, it may be necessary to specify a smaller (achievable) viewing angle for video, compared to the required viewing angle for bi-level graphics.

Electromechanical instruments were often required to provide 30 degrees left and right viewing angle before blockage by the instrument case or bezel became significant. This allowed critical information (not at the very edge of the display) to be cross checked by the other pilot in a side-by-side cockpit.

4.2.1.6.7 Verification of viewing angle.

Viewing angles shall be determined by __________.

VERIFICATION RATIONALE (4.2.1.6.7)

Angles must be verified to insure the display will be visible from the operators location.

VERIFICATION GUIDANCE (4.2.1.6.7)

Measurement or evaluation of design data should be used for verification.

VERIFICATION LESSONS LEARNED (4.2.1.6.7)

3.2.1.6.8 Blemishes.

There shall no visible blemishes on the display face when viewed from the normal viewing distance. Blemishes shall be defined as any area where ____________.

REQUIREMENT RATIONALE (3.2.1.6.8)

Blemishes, or small area non-uniformities, are distracting and esthetically undesirable, and, if large and/or high brightness, can obscure information.

REQUIREMENT GUIDANCE (3.2.1.6.8)

Blemishes include stuck or missing pixels or lines, bubbles, pits, or scratches in glass, and small area nonuniformities in brightness or contrast. The eye is sensitive to "edges," i.e., places where contrast changes over a short distance. Small variations in brightness that do not violate the (large area) uniformity requirement herein are often obvious and objectionable.

The criteria of MIL-E-1 have been used in the procurement of CRT bulbs. Blemishes are sometimes not mentioned in display system specifications, since it is generally understood that visible blemishes are objectionable, and detail blemish criteria should be in the CRT or other display component specifications. Additional blemish specifications relating to the phosphor screens themselves have not been standardized. When present, they are frequently drawn from commercial CRT specifications, or generated in consideration of the needs of the application. In monochrome CRTs, phosphor screen defects are considered and counted the same as defects in the glass. In color CRTs, the screen defects are identified and specified uniquely based on maximum allowable size and number, minimum spacing between blemishes and contrast of the defect with respect to the surround.

For irregular blemishes, their size may be defined as the smaller value given by one of the two relationships,

[1] Size = (Length + Width)/2

[2] Size = Length/10 + 2* Width

The following criteria have been used for an Active Matrix Liquid Crystal Display:

a) Bubbles, transparent or opaque flaws, pits, voids, delaminations, or dark spots shall meet the following criteria:

None exceeding 0.4 mm.

No more than two between 0.25 mm and 0.4 mm, and no less than twelve mm apart.

No more than five between 0.12 and 0.25 mm, and no less than six mm apart.

b) No two failed pixels within a ten-pixel radius of each other (also precludes any failed rows or columns); No more than three failed pixels within a 25 mm circle; Total number of failed pixels shall not exceed 0.01 percent (-0.005 percent in some cases) of all pixels. Any display element within a color pixel that is more than 30 percent brighter or dimmer than similar nearby elements is considered a failure of the pixel.

c) For an array with less than three pixels per mm (76 pixels per inch), no failed pixels are allowed at delivery; Single pixel failures in the field may not require replacement if they do not degrade character or symbol legibility.

REQUIREMENT GUIDANCE (3.2.1.6.8) - Continued

Rectangular targets with contrast of 0.02 are visible when they have an area of 20 x 20 minutes of arc (approx. 4 mm square at 76 cm (30") viewing distance). Targets with contrast = 0.04 are visible when they have an area of 5 x 5 minutes of arc (approx. 1 mm square). (Under laboratory conditions, see "Engineering Data Compendium, Human Perception and Performance", Boff & Lincoln, Armstrong Research Labs, 1988, sect. 1.625.)

REQUIREMENT LESSONS LEARNED (3.2.1.6.8)

A blemish about 2 mm in diameter with contrast of 0.1 darker than its surroundings was observed to be clearly visible and distracting on one display panel.

4.2.1.6.8 Verification for no blemishes.

Verification shall be by __________.

VERIFICATION RATIONALE (4.2.1.6.8)

If any blemishes are visible, they must be assessed to determine if they meet the acceptance criteria.

VERIFICATION GUIDANCE (4.2.1.6.8)

Visual inspection should be used to find any visible nonuniformities. Any nonuniformities found should be measured with a spot photometer to determine compliance.

VERIFICATION LESSONS LEARNED (4.2.1.6.8)

3.2.1.7 Display size.

The active display area shall be at least __________ cm by __________ cm. Rounding of display corners shall not exceed __________.

REQUIREMENT RATIONALE (3.2.1.7)

Display size is specified to assure that it is large enough to assure rapid assimilation of displayed data.

REQUIREMENT GUIDANCE (3.2.1.7)

Display size must be determined first of all on the basis of physical limits of the cockpit or panel on which it is designed to fit. However, after those limits are known, it is important to provide the user the required symbol size, picture size, and clarity stipulated in the resolution paragraph. Use of standard size displays should be at least encouraged, if not directly specified.

REQUIREMENT LESSONS LEARNED (3.2.1.7)

At normal cockpit viewing distances (70-80 cm), video in a 525-line format will generally provide adequate image quality on small displays (less than 15 cm or 6 inches square); however, an 875-line format should be used on larger displays. A higher resolution format, such as the EIA-RS-343 1023-line format, should be used for very large (30-cm to 50-cm) displays.

4.2.1.7 *Verification of display size.*

Compliance with the display size requirements may be determined approximately by measuring the active display area, or by analysis of design data.

VERIFICATION RATIONALE (4.2.1.7)

Approximate display size can be verified by direct measurement. On devices with thick or curved faceplates (like CRTs), measurement will be difficult and evaluation of design data/engineering drawings may be needed.

VERIFICATION GUIDANCE (4.2.1.7)

Verification is normally by measurement.

VERIFICATION LESSONS LEARNED (4.2.1.7)

3.2.1.8 Display color.

The display color shall be __________ when measured in __________ ambient lighting.

REQUIREMENT RATIONALE (3.2.1.8)

Display color must be specified on some systems to insure that equipment built by different contractors or at different times is aesthetically compatible. It is also important in some applications in order to be compatible with standard colors. For color displays, the various colors used must be easily separable and must take into account the "reserved" colors (red and yellow).

REQUIREMENT GUIDANCE (3.2.1.8)

Monochrome airborne CRT displays are generally green because:

a) GY phosphor is very efficient and durable, and happens to produce green light.

b) The human eye is most efficient with green light.

c) Narrow bandpass filters are readily available which pass most of the green light and absorb most of the non-green sunlight, thus enhancing contrast.

d) Green light can be made compatible with night vision goggles (NVGs).

REQUIREMENT GUIDANCE (3.2.1.8)

For CRT applications where a particular phosphor or a particular persistence time is required, they should be inserted. This requirement is generally not needed in situations where color, luminance, frame rate and reliability requirements adequately define phosphor requirements.

Type GY phosphor (designated "P-43" in the old phosphor designation system) is specified in many cockpit CRT applications; it is a high efficiency, bright yellowish-green phosphor with a narrow spectrum light output which works well with wavelength-selective filters and diffraction optics. GJ (P-1), YB (P-3), GX (P-44),and KJ (P-53) are also appropriate in some cases. Color CRTs often use X (P-22) which is available in red, green, and blue formulations. See EIA-TEP-116-B, "Optical Characteristics of CRTs", which covers characteristics of all registered phosphors.

The goal in full color displays is to have the color primaries widely separated (in CIE chromaticity coordinates) and/or provide filtering such that they will stay widely separated when exposed to and mixed with ambient light. Present color CRT projects have simply specified the color coordinates of the most appropriate, currently available phosphors.

LCD matrix displays have inherently different characteristics. For example, the saturation of colors does not change appreciably with ambient light levels on active matrix LCDs (AMLCDs) which have color filters over each subpixel. A color filter is used to give each subpixel its desired primary color, but it also serves to absorb most of the reflected (white) ambient light.

REQUIREMENT LESSONS LEARNED (3.2.1.8)

Specifying the color coordinates of the phosphors on color CRTs has been adequate, since the phosphor colors are widely separated and allow a large gamut of colors to be generated on the CRT, by mixing the primaries in any desired ratio. Where symbology uses color coding, and the operator must be able to easily name the color he sees, regardless of the background or lighting conditions, only a few (5 to 8, depending on which study you believe) uniquely identifiable colors can be used. Color difference criteria (see 3.2.1.6.5) can be used to try to optimize the distribution of the colors used. Colors are generally specified and measured in a dark ambient because this makes testing easier and repeatable, but this ignores the major effects of ambient light on color saturation. See 3.2.1.6.5 for more on this subject.

In color CRT displays, the color coordinate tolerances for the blue phosphor primaries need to be slightly greater than for red or green phosphors due to the chemical sensitivity of the P-22 blue phosphor most widely used. In addition, color coordinates for mixed colors (e.g., cyan, yellow, and white) must be enlarged in order to allow for variations resulting from the combination of color ratioing accuracies (electronic) and variations in individual primary phosphor screen colors.

A color tolerance radius of 0.015 (1976 CIE UCS) units has been suggested where color coding is used on multiple color CRTs in the cockpit. 0.02 units was used on one CRT, and 0.03 units may be the tightest tolerance practical in production for some phosphors (such as P-22 blue).

4.2.1.8 Verification of display color.

Display color shall be measured using __________ in a __________ ambient.

VERIFICATION RATIONALE (4.2.1.8)

Display color must be evaluated to assure that it is fully usable and aesthetically acceptable.

VERIFICATION GUIDANCE (4.2.1.8)

On monochrome CRT systems, review of technical data may be adequate to determine that a standard phosphor of known color is being used. For color CRT systems or systems using other display media, spectroradiometer measurements should be performed to establish chromaticity coordinates of at least the primary colors.

VERIFICATION LESSONS LEARNED (4.2.1.8)

Specific test procedures must acknowledge the limitations (measurement uncertainty) of the measuring instruments. Spectroradiometers will provide the most accurate color measurement, but are also more expensive and complex. At the other extreme, small hand held colorimeters permit rapid color determination, but the accuracy of the measurement depends upon the accuracy with which the color filters and spectral response of the instrument emulates the CIE chromaticity curves. Correction factors have been found useful in the latter case when determined for each color, and provided the colors measured do not vary greatly in color coordinates.

3.2.1.9 Night Vision Imaging System (NVIS) requirements.

The display unit shall be operationally compatible with Class ___________ NVIS and shall not produce an NR value greater than ___________.

REQUIREMENT RATIONALE (3.2.1.9)

Night Vision Imaging System compatibility is required of many avionic displays, whether to allow immediate use of NVGs, to allow for future growth to use NVGs, or to minimize the emission of IR and light from the cockpit to reduce observability.

REQUIREMENT GUIDANCE (3.2.1.9)

MIL-L-87240 provides extensive guidance on aircraft lighting, including a section on NVIS compatibility which includes the compatibility requirements of the tri-service specification MIL-L-85762. The requirements in MIL-L-85762 are most often invoked as specified. However, some tailoring may be appropriate. Some user communities feel the NVIS radiance levels specified in MIL-L-85762 are too stringent for their applications, particularly non-helicopter users. Over- specification of NVIS requirements will constrain other important display parameters, most notably maximum display luminance available for daylight operation. State-of-the-art performance available must be considered to avoid mutual conflicts among maximum luminance and contrast (for daylight readability), color (multi-color vs monochrome) and NVIS (Class A or Class B) performance requirements. Display size may also be a consideration, particularly in raster-scanned CRTs where maximum achievable luminance varies as the inverse of display area.

REQUIREMENT LESSONS LEARNED (3.2.1.9)

MIL-L-85762 establishes limits on radiant power of emissions within the sensitivity envelope of NVIS. Two classes of NVIS are specified, Class A and Class B. The difference in the two is the cutoff point of the minus-blue (long pass) filter used on all third generation aviators NVIS to reduce their response to visible light from the cockpit. 50 percent NVIS response is at approximately 630 nm for Class A and 660 nm for Class B NVIS. Class B NVIS allows limited color capability in the cockpit, but at the expense of reduced sensitivity overall (a consequence of the filter cut-on point). The Class A NVIS radiance limit of 1.7×10^{-10} NVIS Radiance Class A units (NRA) cannot be applied to a multicolor display that uses red and/or yellow. It has been shown to be mathematically impossible to meet the Class A NVIS limit in the presence of such longer wavelength visible emissions. The higher Class B limits were devised specifically for use with color displays.

The standard red and green colors called out in MIL-L-85762 have been used as requirements on electronic displays, but these color requirements only apply to the extent that those displays are used to present warnings and cautions which must be of standard color.

A color CRT operating in a monochrome green mode typically will not meet the Class A requirements due to emission of unselected colors caused by scattered electrons inside the CRT. The P-43 and P-53 green phosphors generally used in monochrome avionic displays also have emissions at longer wavelengths which will cause the display to fail a Class A requirement unless properly filtered. The optical absorption necessary to achieve NVIS compatibility per MIL-L-85762 results in absorption of visible light as well, limiting the luminance achievable in the display. For cockpit displays where luminance is a priority, the NVIS Radiance requirement may force a trade off between maximum luminance and level of compatibility achieved.

Monochrome operation of color active matrix liquid crystal displays also may not meet the Class A requirement because the individual color filters are not sufficiently dense in the IR to attenuate the NVIS Radiance. The pixels of the panel all emit similar amounts of infrared energy whether or not the pixels are activated.

4.2.1.9 Verification of NVIS.

NVIS radiance performance should be evaluated by individuals or organizations that have demonstrated technical competence to the Joint Aeronautical Commanders Group, Tri-Service Lighting Committee, Naval Air Systems Command, Washington DC or to Naval Avionics Center in Indianapolis, IN. Test methods and equipment of __________ shall be used.

VERIFICATION RATIONALE (4.2.1.9)

Compliance must be verified to insure the required low levels of infrared and red emissions are achieved.

VERIFICATION GUIDANCE (4.2.1.9)

Measurement of NVIS compatibility in accordance with MIL-L-85762 is technically challenging if rigorous accuracy is required. There are several means of determining NVIS compatibility with ease of measurement generally inversely proportional to the accuracy required.

The scanning spectroradiometer may be used to obtain best accuracy. However, a very complete understanding of noise thresholds and other error sources is required, as well as means for error mitigation, in order to successfully use this type of system. In particular, significant errors may be made with narrow-band emitting sources, and with test units which have both fixed and variable infrared emissions (e.g., incandescent filament and phosphor screen, respectively, in a CRT).

The MIL-L-85762, Appendix B measuring system performance validation routines intended to demonstrate the fitness of a measuring system to perform NVIS radiance measurements work well if the measuring system is used to measure broad band emission sources (it was developed around filtered incandescent sources).

Spectroradiometer errors can be serious for highly saturated sources such as a P-43 CRT. In cases where the display performance can be mathematically validated to provide radiance levels below the sensitivity threshold of the measuring system, a direct measurement of NVIS radiance is not in itself adequate to determine display compliance. For example, the mathematical evaluation of the individual components that comprise a P-43 CRT (unfiltered emission spectra of the phosphor and spectral transmittance of the contrast enhancement filter designed to provide NVIS compliance) indicate the NVIS performance of the integrated display unit to be below the Class A limit as specified in MIL-L-85762. A direct measurement with a good spectroradiometer will not support this because the detectors aren't sensitive enough (noise level is greater than signal level in parts of the spectrum). Radiance values that are calculated from system noise will indicate a small but finite value of emitted power that is three or more orders of magnitude above the actual performance of the display. The mathematical protocol defined in MIL-L-85762 modifies (amplifies) the small but erroneous power (radiance) and causes the display to be measured non-compliant.

MIL-L-85762 also does not accurately account for sources (such as CRTs and flat panel displays) that have both fixed and variable sources of NVIS-sensitive emissions. In a CRT, as well as in the fluorescent tubes used to backlight LCDs, the hot filament produces relatively constant IR emissions, while the phosphor produces emissions proportional to luminance. MIL-L-85762 allows measuring the display at a brighter setting and then scaling down the results to the specified luminance of 1.7 cd/m^2 (0.5 fL). Since the IR emissions do not go down proportionally, this can allow a display with excessive emissions to pass the test.

The quickest and most straightforward validation method is a direct visual comparison of the test object and a carefully calibrated threshold radiance standard, viewed through a properly filtered GEN III NVIS inspection device (GEN III monocular, for example). The threshold radiance standard must be a device that can be accurately characterized. An NVIS compatible, filtered incandescent light source which has measurable energies at all wavelengths within the NVIS sensitivity envelope is ideal for this purpose.

The GEN III NVIS inspection device must also be carefully characterized by a qualified standards house because the exact characteristics of the minus-blue filter can have a profound effect on the compatibility observations, particularly if the light spectrum of the test object differs significantly from that of the reference standard.

NVIS spot radiance meters may also be used, with more accurate results, when calibrated with a calibrated threshold radiance standard or conventional luminance standard with suitable calibrated attenuators to reduce the light source output appropriately. The spectral output of such a standard need not resemble the unit under test.

VERIFICATION LESSONS LEARNED (4.2.1.9)

3.2.1.10 Video/symbology overlay.

The equipment shall be capable of displaying __________ symbols while displaying video.

REQUIREMENT RATIONALE (3.2.1.10)

Where system requirements necessitate overlay of symbols on video, the appropriate requirements must be specified.

REQUIREMENT GUIDANCE (3.2.1.10)

This requirement applies to systems requiring symbols overlaid on video. The following requirements have been used for a HUD with raster capability: "The equipment shall be capable of displaying all symbols and symbol combinations required herein while displaying video. During display of video, selected symbols may be displayed in raster rather than by stroke. Primary symbols and symbols whose appearance is substantially degraded by being placed in raster shall be displayed by stroke. Use of stroke during retrace may be extended by 'stealing' (deleting) up to 30 lines of video. Such 'line stealing' should be minimized, such that no more video is deleted than necessary at any given time. Symbol quality during display of video shall meet all requirements herein, except that symbols displayed in raster may be degraded as required by the physical limitations of quantifying them into raster lines." This system has both stroke and raster symbol generation capability, which adds significant complexity and may not be needed for other systems.

Where raster symbols are overlaid on video, they must be a shade brighter than the video or be otherwise enhanced (see 3.2.1.6.3). Separate brightness controls for symbology and raster are generally needed to optimize the picture. Gamma, or the non-linear relationship between video signal voltage and desired display luminance, must also be specified in some cases.

REQUIREMENT LESSONS LEARNED (3.2.1.10)

On color CRTs, when the symbols are overlaid on a different color background, the colors of the symbol and background mix, producing another color. This can be avoided by electronically substituting the symbols for video, rather than adding them to the background.

4.2.1.10 Verification of video/symbology overlay.

Video/symbology overlay shall be demonstrated.

VERIFICATION RATIONALE (4.2.1.10)

Proper display of combined video and symbols must be verified.

VERIFICATION GUIDANCE (4.2.1.10)

Verification by demonstration is generally adequate.

VERIFICATION LESSONS LEARNED (4.2.1.10)

3.2.1.11 Video size.

The equipment shall display video from the __________. The __________ aspect ratio raster shall be centered horizontally and subtend at least __________. The center of the raster shall be __________.

REQUIREMENT RATIONALE (3.2.1.11)

The size of the video, if different than the display size, must be defined.

REQUIREMENT GUIDANCE (3.2.1.11)

This requirement applies to systems where video is displayed at other than the exact display size. For example, on a HUD with video capability, the video may fill the instantaneous or total field of view vertically or horizontally, but will not, in general, match the total symbology display area. The paragraph should also specify the location of the video on the display, in terms of degrees below the horizontal datum for a HUD and centimeters from the center on other displays. Where 4:3 or 16:9 aspect ratio video is displayed on a 1:1 screen (or vice versa), this paragraph should describe whether the screen is overscanned in one direction or underscanned in the other direction to make the video fit.

REQUIREMENT LESSONS LEARNED (3.2.1.11)

4.2.1.11 Verification of video size.

Video size shall be measured by __________.

VERIFICATION RATIONALE (4.2.1.11)

Appropriate sizing of video must be verified.

VERIFICATION GUIDANCE (4.2.1.11)

Normally, measurements taken during acceptance test would be adequate.

VERIFICATION LESSONS LEARNED (4.2.1.11)

3.2.1.12 Viewability during gunfire.

During periods of gunfire, any apparent displayed image size change or symbology movement (or combination of both) shall not degrade the pilot's capability to use critical symbology and shall not exceed __________ percent of the jitter values specified herein. The equipment shall return to full performance immediately upon cessation of gunfire.

REQUIREMENT RATIONALE (3.2.1.12)

On aircraft which have a gun, the level of performance during gunfire must be specified.

REQUIREMENT GUIDANCE (3.2.1.12)

This requirement, which actually serves to relax accuracy requirements during gunfire, has been used on F-16 and A-10 HUDs with "200 percent" filled in. Because of the severity and short duration of gunfire, full performance during gunfire may be difficult and expensive to achieve and be of very little value.

REQUIREMENT LESSONS LEARNED (3.2.1.12)

4.2.1.12 Verification of viewability during gunfire.

Degradation of the symbology shall be monitored visually during gunfiring vibration test. If significant degradation occurs, the apparent line width and positional variations shall be measured.

VERIFICATION RATIONALE (4.2.1.12)

Viewability must be verified to assure that the pilot can see critical symbols during gunfire.

VERIFICATION GUIDANCE (4.2.1.12)

Verification is generally done by visual observation backed up by measurements if necessary.

VERIFICATION LESSONS LEARNED (4.2.1.12)

3.2.1.13 Flicker, jitter, and noise.

The display shall not exhibit flicker which is discernible to the eye. Jitter shall be less than __________ (3 sigma). The effects of electrical noise shall not cause any visible distortion, positional or dimensional instability, or luminance variation in any symbology, reticle, or raster and shall not interfere with proper presentation or usability of the display. Motions at frequencies above 0.25 Hz are considered jitter, while lower frequency movements shall meet the requirements of the stability paragraphs herein.

REQUIREMENT RATIONALE (3.2.1.13)

Flicker, jitter, and noise in a display degrades accuracy, can cause confusion or errors in a tense, high workload environment, and are aesthetically objectionable.

REQUIREMENT GUIDANCE (3.2.1.13)

It is always desirable to reduce artifacts in the display, such as flicker, jitter, and noise, to a level that is not noticeable to the operator. Flicker is very difficult to quantify and measure. A properly designed CRT display should have no flicker other than the barely perceptible fading of alternate lines which can usually be seen in an interlaced raster display at high brightness. For other display technologies, more specific flicker criteria may have to be developed. Jitter should be limited to much less than the minimum line width to be displayed. For example, a HUD with a 1-mr nominal stroke width should have less than 1 mr (0.074 cm at 71.1 cm viewing distance) of jitter. In fact it may be limited to much less; for example, ARINC Characteristics 725 limits jitter to 0.018 cm (0.007 inch). Noise which is noticeable when the display is in normal operation should not be allowed, although in some situations (for example, a display for a special project where only a few will be built), the time and cost required to design out all noise may be excessive compared to the aesthetic value of a "clean" display.

Other artifacts include "ripple", "swimming" and "jerking".

"Ripple" is visible as repetitive motion of one part of the display relative to other parts. This can be caused by noise, such as AC power ripple, in the deflection signals on a CRT.

"Swimming" occurs when part of a character or symbol moves relative to the rest of the symbol, making edges waver or fluctuate when the symbol moves or rotates. This can be caused by a display or graphics processor with display increments that are too large.

"Jerking" occurs when a character or symbol moves in increments that are large enough to be visible. This can be caused by input data that is not updated often enough or by a graphics processor with display increments that are too large.

REQUIREMENT LESSONS LEARNED (3.2.1.13)

A standard 30-Hz frame, 60-Hz field (2:1 interlaced) raster video is widely used on CRTs. Stroke-written graphics and computer-generated raster graphics with thin lines are written at 50 Hz or higher - typically 60 Hz non-interlaced for PC monitors. LCDs generally must be driven with symmetric drive voltages; any asymmetry in this system results in flicker at one-half the frame rate, so they must typically be driven above 75 Hz to prevent visible flicker.

4.2.1.13 Verification of flicker, jitter and noise.

The display shall be monitored for visible flicker, jitter, and noise. Any objectionable effects noticed shall be measured.

VERIFICATION RATIONALE (4.2.1.13)

Compliance must be verified for aesthetic and accuracy reasons.

VERIFICATION GUIDANCE (4.2.1.13)

Verification should be based on visible observations backed up by measurements if necessary.

VERIFICATION LESSONS LEARNED (4.2.1.13)

Where the jitter is present in an electronic signal, such as a composite video signal from a signal generator, jitter can be measured by displaying the signal on an oscilloscope synchronized from an accurate time base and comparing the timing of video from line to line and/or frame to frame. Measuring jitter on a display surface is more difficult and might require taking repetitive photographs and comparing them. It is rarely necessary to measure jitter since nearly everyone agrees that visible jitter is objectionable and it is generally possible to design systems so none is visible, in which case it need not be measured.

3.2.1.14 Dimensional stability.

[a] Symbology dimensional stability. The dimensional stability of the symbology shall be ± __________ for symbols less than __________ in height or width and for larger symbols, ± __________ per __________ of height or width.

[b] Raster dimensional stability. The raster shall be dimensionally stable so that in the course of normal operation, during mode switching, or aircraft power variation, the total display image size shall not change more than __________ percent in height or __________ percent in width.

REQUIREMENT RATIONALE (3.2.1.14)

Symbol and raster dimensions must be stable for aesthetic reasons and for accuracy.

REQUIREMENT GUIDANCE (3.2.1.14)

Dimensional stability of ± 1 mr for symbols less than 50 mr in height, and 1 mr per 50 mr in height have been used for HUD symbols. Comparable stabilities for an MFD would be ± 0.7 mm for symbols less than 50 mr in height, and ± 0.7 mm per 50 mr in height. Display image size changes are generally limited to less than ± 2 percent.

REQUIREMENTS LESSONS LEARNED (3.2.1.14)

4.2.1.14 Verification of dimensional stability.

Symbol and test pattern dimensions shall be measured to determine compliance.

VERIFICATION RATIONALE (4.2.1.14)

Dimensional stability must be verified for accuracy and aesthetic reasons.

VERIFICATION GUIDANCE (4.2.1.14)

Verification should be based on measurements.

VERIFICATION LESSONS LEARNED (4.2.1.14)

3.2.1.15 Positional stability.

[a] Symbology positional stability. The positional stability of the symbology shall be ± ____________.

[b] *Raster positional stability. Displayed video data variation shall not exceed ±* ____________ percent azimuth or elevation under any combination of environments.

REQUIREMENT RATIONALE (3.2.1.15)

Symbol and video position must be stable for aesthetic reasons and for accuracy.

REQUIREMENT GUIDANCE (3.2.1.15)

Symbol positional stability of ± 1 mr has been used for a HUD. Stability of raster position of ± 2 percent has been used for a HUD. In some cases where stroke and raster are used on the same display, the registration between the two is more important.

REQUIREMENT LESSONS LEARNED (3.2.1.15)

4.2.1.15 Verification of positional stability.

The position of symbols and video shall be measured to determine compliance.

VERIFICATION RATIONALE (4.2.1.15)

Positional stability must be measured to assure an accurate and aesthetically pleasing display.

VERIFICATION GUIDANCE (4.2.1.15)

Verification is normally done by measurement.

VERIFICATION LESSONS LEARNED (4.2.1.15)

3.2.1.16 Raster distortion and linearity.

No picture element shall be displaced by more than __________ percent of the picture height from its true position referenced from the center of the picture.

REQUIREMENT RATIONALE (3.2.1.16)

Raster distortion must be limited for accuracy and aesthetic reasons.

REQUIREMENT GUIDANCE (3.2.1.16)

Distortion and linearity error requirements of less than 1 percent have been applied to CRT based systems. Distortion of two percent has been allowed for many systems, and is normally adequate.

A distortion requirement is not needed on a fixed matrix display (EL, Plasma, LCD, FED, etc.) where the image is digitally driven to the pixels, thus having no inherent ability to drift or distort.

REQUIREMENT LESSONS LEARNED (3.2.1.16)

Distortion and linearity errors of less than one percent are achievable with modern circuitry. Devices with large optics, such as the Wide Field-of-View (WFOV) HUD, may have serious optical distortion which adds to the display image distortion. Errors which are spread over a large area are much more tolerable than small-area distortions, just as large-area brightness nonuniformities are tolerable.

4.2.1.16 Verification of raster distortion and linearity.

Raster distortion and linearity shall be tested by __________.

VERIFICATION RATIONALE (4.2.1.16)

Raster distortion must be measured to assure accuracy and aesthetic quality.

VERIFICATION GUIDANCE (4.2.1.16)

The "ball" chart defined in EIA-RS-170, has been used for linearity measurements. It is made in the form of a transparency with circles of radius equal to two percent of the display height. This chart is overlaid on a raster containing a grid of white lines; all line intersections should fall within the circles.

VERIFICATION LESSONS LEARNED (4.2.1.16)

3.2.1.17 Reflections.

[a] The relative intensity of second surface reflections visible in the HUD field-of-view shall not exceed ___________ percent of the primary symbol or video luminance.

[b] Reflectivity of the display face shall not exceed ___________ percent.

REQUIREMENT RATIONALE (3.2.1.17)

Secondary reflections must be controlled to prevent reflections from interfering with the primary displayed information.

REQUIREMENT GUIDANCE (3.2.1.17)

The secondary reflection requirement applies to equipment having optics. Secondary reflections have been limited to two percent in current HUDs. This is achievable and reduces interference between secondary reflections and the displayed information.

A limit of 0.5 percent reflectivity on the display face is generally appropriate for displays used in sunshine, and implies that an anti-reflective coating will be used. Note that the contrast requirements herein indirectly require control of reflections, so no reflectivity requirement is needed if a contrast requirement in a specific ambient lighting environment is specified.

REQUIREMENT LESSONS LEARNED (3.2.1.17)

4.2.1.17 Verification of reflections.

Intensity of reflections shall be measured to determine compliance.

VERIFICATION RATIONALE (4.2.1.17)

Reflections must be measured to assure that they are not objectionable.

VERIFICATION GUIDANCE (4.2.1.17)

Verification should be by measurement.

VERIFICATION LESSONS LEARNED (4.2.1.17)

3.2.1.18 Solar effects.

The optical design shall limit images and background illuminations arising from solar illumination to less than ___________ percent of the luminance of the illuminating source when viewed from anywhere within the eye motion box. Continuous direct sun illumination on the equipment within the cone of acceptance shall not result in damage to any sub component whether operating or not.

REQUIREMENT RATIONALE (3.2.1.18)

Solar effects on a HUD must be limited to assure that bright sun images do not interfere with use of the display or degrade the equipment.

REQUIREMENT GUIDANCE (3.2.1.18)

Solar images have been limited to less than 2.5 percent on existing HUDs. Note that 2.5 percent of the sun's brightness is still bright enough to produce a very objectionable sun image in the display, but because the sun is only in the correct place to produce the image a small percentage of the time, and there is often no practical way to prevent the image, it has been accepted. A tighter requirement (0.5 percent) should be a design goal.

REQUIREMENT LESSONS LEARNED (3.2.1.18)

4.2.1.18 Verification of solar effects.

Solar effects shall be measured by __________.

VERIFICATION RATIONALE (4.2.1.18)

Solar effects must be measured to insure display usability.

VERIFICATION GUIDANCE (4.2.1.18)

Measurement techniques appropriate for the display should be inserted.

VERIFICATION LESSONS LEARNED (4.2.1.18)

3.2.1.19 Automatic brightness control and sensor.

An automatic brightness control (ABC) shall be provided to maintain visual contrast on the display as the ambient changes. The range of the ABC shall be suitable for ambient light levels in the range of __________. As a design goal, the ABC shall automatically increase brightness during night mode operation when bright lights are in the operator's forward field of view.

REQUIREMENT RATIONALE (3.2.1.19)

An ABC has been used on displays which are exposed to sudden or frequent changes in ambient light in a high workload environment.

REQUIREMENT GUIDANCE (3.2.1.19)

An ABC suitable for use against ambient backgrounds from 340 to 34,000 cd/m^2 (100 to 10,000 fL) has been used for a HUD. An ABC for a head-down display in a fighter cockpit was specified to be suitable for ambient illuminations from 1,080 to 108,000 lux (100 to 10,000 fc). However, this is a relatively useless range since there is really no need to dim a display in this environment.

Although ABC sounds like a great idea, some implementations have been expensive, difficult to test, and of relatively little value in actual aircraft use. Problems which should be resolved include:

1) Multiple sensors and a hysteresis function are needed to prevent fluctuations due to shadowing, such as by the operators hand.

2) On head-down displays, a forward-looking sensor is needed to account for the pilot's eye adaptation level due to the scene luminance outside (rather than just cockpit illumination). A system that dims displays while sun is shining in the pilots eyes is doomed to failure.

3) Sensors with increased sensitivity are needed to make ABC work in the 1-100 fc range (dusk and dawn transition) where they would be most useful.

4) It is now practical to have software control the brightening and dimming time constants, and the nonlinear relationship between ambient levels, control settings, and display drive signals, but proven algorithms and parameters may not be available.

REQUIREMENT LESSONS LEARNED (3.2.1.19)

The ABC used on the F-15 head-down displays has caused problems and may be eliminated; ABC appears to be most useful on HUDs. ABCs are being used on the Boeing 757/767 commercial aircraft where sensors are provided to measure both the cockpit illumination level and the forward scene luminance. Operation over a wider range (down to 10.8 lux) is desirable but may not be practical with existing technology. Tight tolerances are not necessary.

4.2.1.19 Verification of automatic brightness control (ABC).

Compliance shall be verified by __________.

VERIFICATION RATIONALE (4.2.1.19)

Performance must be evaluated to assure that the ABC provides the required brightness adjustment.

VERIFICATION GUIDANCE (4.2.1.19)

Laboratory brightness tests can be performed to verify that the ABC works as designed. The actual ambient-brightness-versus-display-brightness function must often be determined experimentally during flight test of the hardware, since the desired characteristic is greatly affected by the surroundings in the cockpit. Wide tolerances should be used in this test, since accuracy is difficult to control and of very little value.

VERIFICATION LESSONS LEARNED (4.2.1.19)

3.2.1.20 Warm-up time.

The equipment shall be functionally operational and conform to all accuracy and performance requirements within __________ minutes of being switched on when operated in the environment specified herein, including temperature extremes. Transient power loss for up to __________ seconds shall not require re-warm-up longer than the period of power loss.

REQUIREMENT RATIONALE (3.2.1.20)

Prompt warm-up is required to prevent delays when starting up the aircraft and avoid wasted maintenance time when operating the equipment for checkout or repair.

REQUIREMENT GUIDANCE (3.2.1.20)

A warm-up time of two minutes is generally adequate. Some systems have also allowed degraded performance for up to five or ten minutes after turn-on at cold temperature extremes. Others, such as engine instruments on an aircraft which will be on alert, must provide a reasonable display immediately, or within 30 seconds, but may not need to meet full specifications for two minutes. Power transients of up to one second should be tolerated without requiring a full re-warm-up period.

LCDs do not function at low temperatures and must have built in heaters if the system is to start up quickly in a cold environment. A requirement that is compatible with LCDs but still provides a usable display during aircraft start is:

Display shall have a visible image within 30 seconds (at least 25 percent brightness and 1-Hz update rate) and meet specified performance within 5 minutes when starting at -40°C.

REQUIREMENT LESSONS LEARNED (3.2.1.20)

CRTs have an inherently slow warm-up because of their vacuum tube nature. The major problems associated with warm-up of analog circuitry and mechanical devices have mostly disappeared with current digital hardware.

4.2.1.20 Verification of warm-up time.

Warm-up time shall be measured.

VERIFICATION RATIONALE (4.2.1.20)

Warm-up must be checked to assure that the display equipment does not delay aircraft start-up or maintenance.

VERIFICATION GUIDANCE (4.2.1.20)

Verification is normally done by timing with a stopwatch.

VERIFICATION LESSONS LEARNED (4.2.1.20)

3.2.1.21 Controls.

Controls for brightness, contrast, and __________ shall be provided. Brightness and contrast shall change logarithmically with linear control movement, to give the subjective impression of linear control.

REQUIREMENT RATIONALE (3.2.1.21)

Several controls are normally included on display equipment. Brightness and contrast are required to make the display characteristics compatible with the ambient lighting.

REQUIREMENT GUIDANCE (3.2.1.21)

Nearly all displays have rotary type controls for brightness and contrast, plus several other controls depending on the system application and configuration. MIL-STD-1472 contains guidance on controls. See also 3.3.3.

"Bezel buttons" (also called "soft keys") like the ones found on automated teller machines, are used on most multi function displays. Ten to twenty-four programmable switches are arranged around the periphery of the display, with the label presented on the display adjacent to the switch.

Advantages of bezel buttons are:

a) Minimum hardware to buy and maintain

b) Minimum panel space occupied

c) Switch labels and functions can be changed in software as design is refined or functions are added

d) Less finger prints on glass (compared to touch panels)

e) Tactile feedback (click) when buttons are pushed

Disadvantages are:

a. Stuck with one switch arrangement

b. Pushbuttons are not optimum for functions previously performed by rotary switches.

c. No shape coding of switches

d. Adds clutter to the video screen

"Soft knobs" have also been used, providing a multi-function control for easy adjustment of functions traditionally controlled by a rotary control.

Separate video contrast, video brightness and symbol brightness controls are provided on many MFDs. Others have the relationship between video and symbol brightness fixed (set) by the design. If it is set, it must be changeable (by software or hardware adjustment) since the desired relationship depends upon the lighting environment and the video sources being used, and has had to be adjusted as a result of flight tests.

"Ganged" brightness controls, which adjust several displays at once, are used in some cases where there are several electronic displays of the same technology (similar dimming characteristics) in the cockpit, much as the traditional flight instruments lighting was ganged together.

REQUIREMENT LESSONS LEARNED (3.2.1.21)

Modern display units use push buttons, rocker switches, or "digital potentiometers" to adjust brightness, contrast, etc. This technique will result in discrete steps in control settings, which can be objectionable unless the steps are made sufficiently small. These devices eliminate the reliability problems of potentiometers. Also, they output increment and decrement signals rather than an actual value, which allows previous settings to be retained and reset automatically by software when modes or formats are changed.

4.2.1.21 Verification of controls.

Operation of all required controls will be demonstrated.

VERIFICATION RATIONALE (4.2.1.21)

Availability of controls and smooth, easy operation must be verified.

VERIFICATION GUIDANCE (4.2.1.21)

Verification is generally done by demonstration of the operation of the controls.

VERIFICATION LESSONS LEARNED (4.2.1.21)

3.2.1.22 Nuclear survivability.

Nuclear survivability shall be in accordance with ___________.

REQUIREMENT RATIONALE (3.2.1.22)

This requirement applies to equipment used on aircraft which are required to operate in a nuclear environment.

REQUIREMENT GUIDANCE (3.2.1.22)

Characteristics of the nuclear effects which will be felt in the area where the equipment is installed should be determined and used in the specification. See also MIL-STD-1799.

REQUIREMENT LESSONS LEARNED (3.2.1.22)

Nuclear effects generally apply to strategic aircraft, but have not been applied to tactical aircraft. Nuclear hardening or shielding will affect cost, weight, choice of materials, etc.

4.2.1.22 Verification of nuclear survivability.

Nuclear survivability or vulnerability shall be evaluated by __________.

VERIFICATION RATIONALE (4.2.1.22)

Mission-critical displays must be tested to verify that they will continue to operate.

VERIFICATION GUIDANCE (4.2.1.22)

Appropriate tests must be developed.

VERIFICATION LESSONS LEARNED (4.2.1.22)

3.2.1.23 Processor standards.

General purpose processors shall use the __________ instruction set and be programmed in __________ language. Processor configuration and programming techniques shall comply with __________. Software which controls symbol format shall be contained in __________ memory devices, to allow flexibility of symbol format with minimal impact on the display hardware. Specialized processors and languages may be used for specific display generation tasks which cannot be done with standard general purpose processors.

REQUIREMENT RATIONALE (3.2.1.23)

Processor and software design characteristics are specified to promote commonality of hardware and software and the support equipment and training associated with them.

REQUIREMENT GUIDANCE (3.2.1.23)

The goal is to use the minimum number of different instruction sets and languages to minimize the cost of supporting computer software in the field. Ada language is required by law except where specific circumstances make this impractical. A software specification or other software coding document should be referenced which defines the numerous other software design requirements. Software which controls symbol format should be contained in ultraviolet or electrically erasable PROM's, since it generally gets changed as a result of flight tests and changes to the aircraft or its mission.

The standard processor and higher order language requirement should apply to the general purpose processor portion of a symbol generator and not necessarily to the specialized hardware and software that converts the symbol commands into display primitives. The specialized software and hardware must operate in a high speed, real time environment to generate all the symbology in the required time. Hardware optimized for symbol generation and assembly language software or micro code optimized for speed is often used for this portion of the symbol generator.

REQUIREMENT LESSONS LEARNED (3.2.1.23)

Special-purpose PALs and ASICs are often used in display processors.

4.2.1.23 Verification of processor standards.
Processor characteristics shall be verified by ___________.

VERIFICATION RATIONALE (4.2.1.23)

Compliance must be verified to assure that the processor and software can be efficiently maintained.

VERIFICATION GUIDANCE (4.2.1.23)

Processor type can often be verified by inspection of documentation if it is a mass-produced type. PROM type can be verified by evaluation of design data.

VERIFICATION LESSONS LEARNED (4.2.1.23)

3.2.1.24 Damage protection/Overload protection.
The equipment shall be protected from chain reaction failures including those from external power switch off or overloads during installation, test, or other causes and _______. Insofar as practical, no damage to an LRU shall result from open circuits or grounding of wiring external to the LRU.

REQUIREMENT RATIONALE (3.2.1.24.1)

Induced failures caused by overload can be greatly reduced by appropriate equipment design.

Equipment containing a CRT must have CRT protection to prevent damage to the CRT.

REQUIREMENT GUIDANCE (3.2.1.24.1)

Use of features such as "crowbar" protection on power supplies may be specified.

Equipment containing CRTs must be designed such that the CRT is undamaged in the event of failure or switch-off of the aircraft electrical power supplies or sweep circuitry. The protection should be effective over the total brightness range.

Equipment containing high voltage should be designed to preclude damage to components or hazards to personnel from high voltage power supply and CRT high voltage arcs by use of arc suppressers or equivalent.

REQUIREMENT LESSONS LEARNED (3.2.1.24.1)

4.2.1.24 Verification of damage protection/overload protection.
Compliance shall be verified by ___________.

VERIFICATION RATIONALE (4.2.1.24)

Compliance must be verified to assure that excessive failures are not induced by overload.

VERIFICATION GUIDANCE (4.2.1.24)

Demonstrations or analysis of circuitry should be performed.

VERIFICATION LESSONS LEARNED (4.2.1.24)

3.2.1.25 *Head-up display (HUD) - specific requirements*

See subparagraphs.

4.2.1.25 Verification of HUD specific requirements

See subparagraphs.

3.2.1.25.1 HUD field-of-view (FOV).

The HUD shall have a total field of view of at least __________ vertical (V) by __________ horizontal (H). The Instantaneous FOV (IFOV) (total seen by both eyes) shall be at least __________ V x __________ H. The FOV and its relationship to the horizontal datum shall be as described in __________. The above requirements are to be met with the eyes centered on the design eye. The total FOV shall be viewable from within the eye motion limits (box) shown in __________ and the IFOV shall not decrease to less than 75 percent of the above requirement with up to __________ cm of eye displacement around the central line of sight within the eye motion box.

REQUIREMENT RATIONALE (3.2.1.25.1)

HUD FOV must be large enough to accommodate display of all necessary information.

REQUIREMENT GUIDANCE (3.2.1.25.1)

This requirement applies to Head-Up Displays (HUDs) only. (Note: "Head" is singular; pilots have only one.) The above paragraph was used in a wide FOV raster HUD specification with the following requirements filled in: 20 degrees vertical, 25 degrees horizontal, 17 degrees x 25 degrees IFOV, relationship to datum shown in a figure, and 1.9-cm (3/4-inch) eye motion allowed. The contractor met the requirements using a diffraction optics combiner. Conventional HUDs (refractive optics) generally have a smaller TFOV and a much smaller IFOV, due to optical limitations. A typical conventional HUD might have a 20-degree TFOV, and a 9-degree by 14-degree IFOV. The maximum TFOV and IFOV obtained from a demonstrated, practical HUD with conventional optics has been 25 degrees and 13 x 20 degrees, respectively.

Conventional optics HUDs with their smaller FOV are adequate for use with weapons which must fire forward (near the aircraft axis). WFOV capability is useful for firing off-axis weapons, and is critically important (along with a video capability) to a system which relies on HUD FLIR video for night navigation (such as LANTIRN).

A guidebook called "HUDs in Tactical Cockpits", written by Jerry Gard of Kaiser Electronics, gives extensive advice on HUD FOV. A Crew Station Ergonomics Information Analysis Center (CSERIAC) State of the Art Report (SOAR) 92-2, "Human Factors Issues in Head-Up-Display Design: The Book of HUD", by Daniel Weintraub and Michael Ensing, provides extensive background on HUDs.

REQUIREMENT LESSONS LEARNED (3.2.1.25.1)

For the F-16 LANTIRN HUD program, data measured in a real cockpit showing eye location at various times for various operators was used to define a "box" 7 cm high, 14 cm wide, and 25 cm long inside which the operator's eyes remained most of the time. Field of view and luminance degradation limits were then specified for the operators eyes in the box. It is essential that the HUD design be based on actual operator's eye positions, measured in a cockpit, rather than the hypothetical "design eye" point. This is particularly important for a HUD which has optical power in the combining glass (e.g., a WFOV diffraction optics HUD) because the ideal viewing position for these HUDs can only be changed by redesigning the optics. With the more traditional HUDs (flat plate combiner glass) it is possible to modify the combiner to adjust the viewing position.

The interaction of the HUD, the design eye position, and the aircraft canopy requires study and optimization. Some of these issues are discussed in Report AFAMRL-TR-83-095, "Optical and Human Performance Evaluation of HUD Systems Design".

At least one aircraft has used the inside of the windshield as the HUD combiner, but this has proven difficult because:

a) It is too far from the pilot and not at the optimum angle to get adequate FOV.

b) Modern aircraft canopies are curved.

c) Alignment and accuracy are hard to maintain, since other optics need to be precisely positioned relative to the combiner, and the windshield bends under air loads and with heating.

Note that General Motors uses the windshield as a combiner in their automotive HUD, where cost savings and aesthetics are more important than accuracy or FOV.

4.2.1.25.1 Verification of HUD field of view (FOV).

Measurements of look angles from specified eye positions to field positions shall be used to determine compliance.

VERIFICATION RATIONALE (4.2.1.25.1)

FOV must be measured to assure that it is large enough for the appropriate symbology and/or video.

VERIFICATION GUIDANCE (4.2.1.25.1)

Verification is normally based on measurements taken with a theodolite.

VERIFICATION LESSONS LEARNED (4.2.1.25.1)

3.2.1.25.2 Parallax.

For a single display element in elevation and azimuth for two eyes 6.35 cm (2.5 inches) apart laterally, 90 percent of the measured values shall not exceed the following: ___________ mr vertically , ___________ mr horizontally converging, and ___________ mr horizontally diverging. No values shall exceed 1.1 times these values. All eye position and field angle data used to satisfy the HUD field-of-view requirement shall be the basis for compliance with this requirement.

REQUIREMENT RATIONALE (3.2.1.25.2)

Parallax must be limited to prevent eyestrain, double imaging, and loss of (or a false sense of) depth perception. Parallax is defined as the difference in viewing angle between the two eyes when they are both looking at the same point or object. For example, two eyes 6.35 cm apart looking at a point 28.5 meters away will be converging 2.3 mr.

Imperfections in the HUD optics and/or the aircraft windscreen cause either the HUD symbology, the real world or both to not be displayed at an optical distance of infinity (from the pilot's point of view). Since the two eyes cannot simultaneously fuse two images that are at different optical distances (i.e., where the difference in the distance exceeds the tolerance of Panum's area) either the HUD symbology or the real world scene, whichever isn't being fixated upon at the time, will appear doubled. The eyes must then accommodate back and forth between the two sources of visual information, resulting in eye fatigue.

REQUIREMENT GUIDANCE (3.2.1.25.2)

This requirement applies to equipment which has optics, including HUDs and Helmet Mounted Displays. Parallax limits of 1 mr vertical, 2.3 mr horizontally converging, and 1 mr horizontally diverging have been used on a HUD, and are usually considered adequate.

REQUIREMENT LESSONS LEARNED (3.2.1.25.2)

Some aircraft require that the HUD have optical power to compensate for the optical power of a curved canopy. In a simple case (the F-15), this is a very slight cylindrical curve ground into the combiner glass. The F-16 has a much more complicated situation because the canopy is a non-uniform compound curve, and has slight optical power. When the Wide Field of View LANTIRN HUD was installed in the F-16, problems with loss of depth perception and double imaging occurred. Anyone designing a similar system should research the work which was done at WPAFB to correct these problems, as it involved tighter windshield specifications, optical modifications to the HUD, and different parallax requirements (ASD-TR-83-5019).

4.2.1.25.2 Verification of parallax.

Eye position and field angle data shall be taken to determine compliance.

VERIFICATION RATIONALE (4.2.1.25.2)

Parallax must be measured to assure that excessive eyestrain, double imaging, or loss of depth perception will not occur.

VERIFICATION GUIDANCE (4.2.1.25.2)

Verification should be based on measurements.

VERIFICATION LESSONS LEARNED (4.2.1.25.2)

3.2.1.25.3 HUD standby reticle.

A standby reticle shall be provided which meets the size and shape requirements of ___________. It shall be independent of ___________. It shall be manually depressible and shall meet the following detail requirements.

[a] Luminance: The reticle line luminance shall be such that the projected images shall be visible and achieve a contrast of at least ___________ against a background luminance of 34,000 cd/m^2 (10,000 fL) and equivalent color temperature of 3,000 to 5,000 Kelvins. The average luminance of the projected image shall be a minimum of ___________ cd/m^2 when viewed through the combining glass.

[b] Line widths. Standby reticle line width shall be ___________ mr when measured at the 50 percent intensity points with the reticle luminance set at ___________ cd/m^2 at the combining glass.

[c] Color. The color of the standby reticle shall lie at UCS 1976 coordinates ___________ and ___________.

REQUIREMENT RATIONALE (3.2.1.25.3)

Until recently, a standby reticle has been required on most HUDs that have a targeting function. Higher reliability of modern electronics, and complexity of having duplicate image sources in a HUD, are making this a high cost, low value option in new systems.

REQUIREMENT GUIDANCE (3.2.1.25.3)

The standby reticle was generated by a mechanical mask and a light bulb, completely independent of the HUD electronics and CRT, in most HUDs built prior to 1980. The complexity of fitting these mechanical components into the optical train added significant cost and degraded reliability, so more recent HUDs have used an independent electronics channel to generate a standby reticle on the same (primary) CRT. This was particularly important on LANTIRN because diffraction optics are used in the combiner and the wavelength of the light source is critical. The level of independence of the standby reticle has generally been established by the users, who naturally want it as independent as possible. The size and shape of the reticle should be defined by a figure included in the specification. It should look like the primary aiming reticle and/or follow the standby reticle guidance.

An alternative to providing a separate standby reticle is to configure the system such that the display will be driven by a backup symbol generator in the event of HUD electronics unit failure. This is particularly attractive in systems which have multiple symbol generators (for head-down displays) which can drive the HUD in a backup mode. It provides a full performance backup mode, rather than the relatively useless manual standby reticle.

A contrast of 0.2 (contrast ratio of 1.2:1), and a minimum luminance of 5,440 cd/m^2 (1,600 fL) has been used and is adequate to assure viewability in sunshine. A contrast of 0.5 would be preferred, but requires serious compromises in other CRT characteristics with current technology.

Reticle line width should be similar to that of the primary symbology; 1 mr width measured at 5440 cd/m^2 (1,600 fL) luminance has been used successfully.

Standby reticles were red in many older HUDs, apparently to distinguish the standby from the primary. With the superior capability of symbol generators today, it will be obvious if a backup reticle is in use. HUDs using wavelength selective optics (diffraction or "holographic" combiners) will only work with one color of light, so it is necessary to make the standby reticle the same color as the primary. Unless a specific color requirement is known, the color requirement should be deleted or a statement that the standby is similar in color to the primary can be used.

REQUIREMENT LESSONS LEARNED (3.2.1.25.3)

4.2.1.25.3 Verification of HUD standby reticle.

Standby reticle luminance, line width, and color shall be measured.

VERIFICATION RATIONALE (4.2.1.25.3)

Standby reticle characteristics must be measured to assure that an aesthetically pleasing and clearly visible reticle is provided.

VERIFICATION GUIDANCE (4.2.1.25.3)

Measurements should be made using the same techniques as those used in measuring primary symbology.

VERIFICATION LESSONS LEARNED (4.2.1.25.3)

3.2.1.25.4 HUD accuracy.

The accuracy of the placement of fire control and navigation cueing symbology on the HUD combiner glass shall be adequate for maximum effective use of the __________ and the following:

[a] Calculated errors shall be based on 3σ values where normal distribution is assumed.

[b] The errors shall include input signal conversion and computational errors in the HUD.

[c] The errors shall be measured relative to the HUD mounting surface.

[d] Static errors shall be computed as the root mean square of azimuth and elevation component errors.

[e] Input signals are assumed to be perfect.

[f] Accuracies are with no canopy in place, except for the symbols listed under "canopy distortion compensation." Accuracy of placement of primary HUD symbols on the combiner shall not exceed ± __________ mr within a __________ diameter circle and ± __________ mr everywhere in the TFOV.

REQUIREMENT RATIONALE (3.2.1.25.4)

Accuracies must be established to insure that HUD symbols allow accurate targeting and to insure that flight and navigation symbols are geometrically correct.

REQUIREMENT GUIDANCE (3.2.1.25.4)

The name of the equipment requiring the greatest accuracy should be inserted; for example, on the A-10, the GAU-8 gun requires that the gun cross be accurately located. Accuracies of ± 1.7 mr on the optical axis, ± 3 mr within a 12-degree diameter circle, and ± 5 mr anywhere in the FOV have been achieved.

REQUIREMENT LESSONS LEARNED (3.2.1.25.4)

4.2.1.25.4 Verification of HUD accuracy.
Accuracy of symbols and symbol positions shall be evaluated by __________.

VERIFICATION RATIONALE (4.2.1.25.4)

Symbol accuracy must be measured to assure that the HUD design provides accuracy adequate for flight control and weapon delivery.

VERIFICATION GUIDANCE (4.2.1.25.4)

Symbol positions are normally measured in the laboratory using a theodolite with the HUD display unit mounted on a precision test fixture. Digital readouts and scales are evaluated by observation.

VERIFICATION LESSONS LEARNED (4.2.1.25.4)

3.2.1.25.4.1 Flight symbol accuracies.
The equipment shall reproduce flight symbol input signals on the display to the following accuracies: __________.

REQUIREMENT RATIONALE (3.2.1.25.4.1)

Primary flight symbols must accurately depict attitude, heading, etc., to prevent the pilot from being disoriented.

REQUIREMENT GUIDANCE (3.2.1.25.4.1)

The following flight symbol accuracies are achieved on the F-16 HUD:

a) Pitch angle: ± 1.0 degree

b) Airspeed: ± 2 KIAS

c) Altitude: ± 7.62 m (25 feet)

d) Roll attitude: ± 1.5 degrees

e) Mach: ± 0.02 Mach

f) Heading: ± 1 degree

REQUIREMENT LESSONS LEARNED (3.2.1.25.4.1)

4.2.1.25.4.1 Verification of flight symbol accuracies.
The requirements of 4.2.1.25.4 apply.

3.2.1.25.4.2 Algorithm accuracies.

The algorithms used to compute fire control symbology locations shall have the following accuracies: __________.

REQUIREMENT RATIONALE (3.2.1.25.4.2)

For a HUD which performs weapon aiming and flight director calculations, the accuracy of the algorithms must be controlled to assure proper weapon delivery and flight director operation.

REQUIREMENT GUIDANCE (3.2.1.25.4.2)

The following accuracies are achieved in the F-16 HUD (excluding display errors):

a) Snapshoot: $\pm$ 0.5 mr

b) Lead computing optical sight: $\pm$ 0.5 mr

c) Flight director: $\pm$ 0.5 mr

REQUIREMENT LESSONS LEARNED (3.2.1.25.4.2)

4.2.1.25.4.2 Verification of algorithm accuracies.

The requirements of 4.2.1.25.4 apply.

3.2.1.25.4.3 Symbol/video registration error.

When symbols are overlaid on the video images, they shall be registered to within __________ percent of the display width, plus __________ percent of the distance from FOV center vertically and horizontally with respect to the commanded true position within the video scene.

REQUIREMENT RATIONALE (3.2.1.25.4.3)

For systems which overlay video with symbology the relative position must be controlled; this is only important for a display where the spatial relationship between the video and symbology has meaning.

REQUIREMENT GUIDANCE (3.2.1.25.4.3)

Alignment of $\pm$ 1 mr 0.5 percent of the distance from FOV center was specified for the LANTIRN HUD. This only applied to the symbols whose exact position in the scene was important.

REQUIREMENT LESSONS LEARNED (3.2.1.25.4.3)

This paragraph is intended to deal with errors occurring within the display system; a system displaying sensor video on a HUD or HMD will have misregistration relative to the real world due to the fact that the camera is not in line with the HUD. For example, a FLIR mounted under the nose is several feet vertically below the HUD, and the image can only match with the real world (from the pilot's point of view) at one range.

4.2.1.25.4.3 Verification of symbol/video registration error.

The requirements of 4.2.1.25.4 apply.

3.2.1.25.4.4 Standby reticle positional accuracy.

The same accuracy requirements stated for the primary reticle shall apply for the standby reticle except ___________.

REQUIREMENT RATIONALE (3.2.1.25.4.4)

If a standby reticle is provided, its accuracy must be specified to assure it will be useful.

REQUIREMENT GUIDANCE (3.2.1.25.4.4)

Standby reticle accuracy is normally equivalent to the primary reticle accuracy.

REQUIREMENT LESSONS LEARNED (3.2.1.25.4.4)

4.2.1.25.4.4 Verification of standby reticle positional accuracy.

The requirements of 4.2.1.25.4 apply.

3.2.1.25.4.5 Combiner glass displacement error.

The combining glass shall not cause real world objects to be displaced by more than ___________ mr (3 sigma) in the area within 5 degrees of the center of the FOV or ___________ mr within the total FOV.

REQUIREMENT RATIONALE (3.2.1.25.4.5)

A HUD combiner glass must have flat and parallel surfaces in order to prevent displacement of the real-world scene.

REQUIREMENT GUIDANCE (3.2.1.25.4.5)

Errors of 0.6 mr in the central part of the FOV, and 0.8 mr overall, are specified for the F-16.

REQUIREMENT LESSONS LEARNED (3.2.1.25.4.5)

4.2.1.25.4.5 Verification of combiner glass displacement error.

The requirements of 4.2.1.25.4 apply.

3.2.1.25.4.6 Combining glass distortion error.

The combining glass shall not cause real world objects of less than 25 mr subtense to be distorted by more than ___________ mr from the true object geometry, established without the combining glass. The distortion requirement shall apply for all eye positions that are required to obtain the total FOV.

REQUIREMENT RATIONALE (3.2.1.25.4.6)

Combiner glass surfaces must be flat to prevent geometric distortion, which degrades appearance and accuracy.

REQUIREMENT GUIDANCE (3.2.1.25.4.6)

Distortion of 0.25 mr is used in the F-16 HUD specification. Larger distortions are allowed in some cases, such as at the discontinuity between the two images on a dual-combiner HUD.

REQUIREMENT LESSONS LEARNED (3.2.1.25.4.6)

4.2.1.25.4.6 Verification of combining glass distortion error.

The requirements of 4.2.1.25.4 apply.

3.2.1.25.4.7 Boresighting.

The HUD display unit shall be designed to provide simple, reliable preboresighting such that when installed in the air vehicle, a combined boresight accuracy of __________ mr (3 sigma) shall be achieved. Alignment, interface matching, or adjustment of the HUD projection unit shall not be required when this unit is removed and replaced after the original factory installation is complete, providing that its mounting assembly is not disturbed.

REQUIREMENT RATIONALE (3.2.1.25.4.7)

For head-up displays, boresighting is required for accurate symbology positioning. Accurate preboresighting, with no on-aircraft adjustments, reduces maintenance costs and allows HUD replacement to be done quickly without special equipment.

REQUIREMENT GUIDANCE (3.2.1.25.4.7)

Preboresighting should not be applied if extremely accurate boresighting is required, since it creates many design constraints. This requirement was applied to the F-16, and made a normal HUD swap-out very easy. However, it is now a major operation to check or reset the factory alignment of the mounting base when it is found to be bad (due to airframe bending).

Where an error budget has been established which goes down to the level of HUD boresight, the appropriate number should be inserted. Alternately, where a system contractor is responsible for accuracy, HUD accuracies should be specified relative to aircraft reference, and the boresight accuracy requirement can be dropped to allow the manufacturer to set up his own error budget.

REQUIREMENT LESSONS LEARNED (3.2.1.25.4.7)

Electronic boresighting is now practical. It can eliminate the need for a mechanically complex and expensive adjustable mounting tray. This method uses an electronic memory on the aircraft to store alignment numbers which are read by the display at power-up and used to adjust symbol positions.

4.2.1.25.4.7 Verification of boresighting.

The requirements of 4.2.1.25.4 apply.

3.2.1.25.5 Canopy distortion compensation.

The system shall compensate the position of the following symbols for optical deviations through the aircraft canopy: __________.

REQUIREMENT RATIONALE (3.2.1.25.5)

Where a curved canopy is used which introduces significant distortion, it may be necessary to electronically shift the position of symbols on the HUD or HMD to make them accurate relative to the distorted real scene.

REQUIREMENT GUIDANCE (3.2.1.25.5)

This requirement is often not needed, since it only applies to HUDs or HMDs in aircraft with curved canopies, such as the F-16. AFGS-87266, Aircraft Cockpit Transparency System, should be referenced for other canopy-related requirements.

REQUIREMENT LESSONS LEARNED (3.2.1.25.5)

Symbol position compensation is used in the F-16. The corrections are done by the HUD processor using a nine-coefficient polynomial correction equation. The coefficients are determined from measurements taken on each windshield when it is manufactured, and are stored in the aircraft computer along with other aircraft weight and configuration data; they are passed to the HUD over the data bus when the system is turned on. This seems to be the most practical way to make the corrections, even though it adds significant complexity to the software. All symbols which must align with the outside scene, such as aiming reticles, target designators, continuously computed impact line, and radar search cues, are compensated. Some aircraft also require compensation to correct parallax errors caused by the canopy. (See 3.2.1.25.2.)

4.2.1.25.5 *Verification of canopy distortion compensation.*

The intentional displacement of symbols for distortion compensation shall be evaluated by ___________.

VERIFICATION RATIONALE (4.2.1.25.5)

Position correction must be tested to insure that the system provides adequate weapon accuracies.

VERIFICATION GUIDANCE (4.2.1.25.5)

A test should be performed to measure the corrections made by the HUD and compare them with the corrections mathematically defined by the equations.

VERIFICATION LESSONS LEARNED (4.2.1.25.5)

3.2.1.25.6 HUD combiner wind loads.

The combining glass and its mounting structure shall withstand without breakage the wind loading and temperature differentials associated with the sudden removal of the canopy in flight. The operational environment preceding removal of the canopy is the normal cockpit environment. Immediately following removal, the wind loading on the combiner will be ___________ and the surface temperature will increase immediately to ____________ °C.

REQUIREMENT RATIONALE (3.2.1.25.6)

This requirement applies only to aircraft in which the front part of the canopy is removed prior to emergency ejection. The HUD must withstand the wind loads in order to avoid breaking up and injuring the pilot.

REQUIREMENT GUIDANCE (3.2.1.25.6)

The F-16 HUD was designed to withstand the wind loads which were determined by analysis and wind tunnel tests and were described in a figure in the specification. Specific loading requirements depend on the maximum safe ejection speed for the aircraft. Consult with escape system and canopy engineers to establish appropriate requirements.

REQUIREMENT LESSONS LEARNED (3.2.1.25.6)

4.2.1.25.6 Verification of HUD combiner wind loads.

Force and temperature loading equivalent to those shown in __________ shall be applied to the HUD combiner. Breakage of the combiner or its mountings shall constitute failure of the test.

VERIFICATION RATIONALE (4.2.1.25.6)

Combiner strength must be verified to assure pilot safety.

VERIFICATION GUIDANCE (4.2.1.25.6)

Static force tests or a dynamic wind-tunnel test should be performed.

VERIFICATION LESSONS LEARNED (4.2.1.25.6)

3.2.1.25.7 HUD combiner transmission and reflection.

The HUD combining glass shall conform to __________. Transmissibility shall be a minimum of __________ percent for both directions through the glass. The outer surface of the combining glass shall have a reflectivity of __________ percent or less.

REQUIREMENT RATIONALE (3.2.1.25.7)

For HUDs, the optical characteristics of the combiner glass are important to provide comfortable, accurate viewing.

REQUIREMENT GUIDANCE (3.2.1.25.7)

This requirement applies only to HUDs. Transmissibility of 70 percent, and outer surface reflectivity of 0.5 percent are appropriate.

REQUIREMENT LESSONS LEARNED (3.2.1.25.7)

For aircraft where NVGs will be used, the transmission of the combiner in the near IR range should also be specified.

4.2.1.25.7 Verification of HUD combiner transmission and reflection.
Measurements shall be taken or procurement data shall be evaluated to determine compliance.

VERIFICATION RATIONALE (4.2.1.25.7)

Compliance must be verified to assure adequate performance and appearance of the combiner.

VERIFICATION GUIDANCE (4.2.1.25.7)

Verification can be done by measurement or data evaluation.

VERIFICATION LESSONS LEARNED (4.2.1.25.7)

3.2.1.26 Helmet mounted display (HMD)-specific requirements.
A HMD system with the following characteristics shall be provided: ___________.

REQUIREMENT RATIONALE (3.2.1.26)

A HMD system could be valuable for air-to-air and air-to-ground attack, low level terrain following missions, night and in-weather missions, night rescue, and special operations. It can provide the pilot with an overlay of both video and graphics information from sensor-generated and computer-generated sources and maintain the pilot's temporal and spatial relationships to the tasks at hand. It can provide the pilot with an instantaneous presentation of the tactical and portions of the strategic situation to improve the pilot's situational awareness and reduce workload. Through the use of EO, FLIR, and LLTV sensors used separately or in combination through appropriate signal processing, the HMD presentation can permit the pilot to fly with improved safety and allow him to detect/acquire objects at long range.

REQUIREMENT GUIDANCE (3.2.1.26)

Because of the lack of existing successful production HMD systems to provide a "baseline" of performance requirements, this section is necessarily vague.

Existing HMDs typically added excessive weight and volume to the helmet and did not have the proper CG or wind blast resistance for safe ejection, although some experimental units now are considered ejection-safe. Monocular, symbology-only systems can be made bright enough for use in sunshine, while current technology makes it very difficult to provide video in sunlight. Video, with its high spatial frequency information, can cause binocular rivalry, and is thus more compatible with a binocular viewing configuration.

It is common practice to refer to a head-mounted system that can display raster video and/or dynamic stroke symbology as a Helmet Mounted Display (HMD). Head-mounted systems that can only display fixed symbols are referred to as Helmet Mounted Sights (HMS).

Current HMD systems use a miniature CRT, about 12 to 25 mm (1/2 to 1 inch) in diameter, to provide a video image on the helmet. HMSs use a smaller device, such as a pattern of light-emitting diodes (LEDs) to form a reticle. Installing a 1-inch CRT on the helmet adds significant weight, due to the weight of the glass CRT bottle, high-voltage connections, etc., so attempts are being made to build smaller CRTs with adequate performance. Providing high resolution, high brightness, ruggedness, and producibility in a 1-inch CRT is already very difficult, so meeting the same requirements in a smaller tube will be even more difficult, and will almost certainly result in loss of performance in some areas. Alternatives are being investigated. For example, small liquid crystal displays (LCDs) could solve the size and weight problem but introduce new problems in resolution; addressability; producibility; the need for a powerful, uniform backlight; and the need for an extremely high-contrast-ratio image source if one is to see through the background. Systems have been tested which locate the CRT remote from the helmet; the image is then carried to the helmet with a fiber optic cable. This allows the use of a larger CRT, mounted in a box where its full performance can be realized, but requires the use of an image-carrying fiber optic cable, with serious size, stiffness, weight, and resolution problems, and the addition of another box in the cockpit. The fiber optic cable approach has been used in an "NVG HUD", a device which is added to existing NVGs and provides symbology overlaid on the NVG images, but does not have adequate resolution to display video and is not integrated into an ejection-safe design.

Additional guidance is available in laboratory reports (for example, Kocien, 1991).

The field of view discussion in the HUD section of this handbook also generally applies to HMDs. While attempts are being made to achieve very wide FOV (over 50 degrees) in HMDs, this is only necessary if the intent is to fully immerse the pilot in the artificial image in the HMD. For more typical cases where the HMD information is only a supplement to the real-world view (such as providing off-boresight missile aiming) a small FOV may be adequate - 15 degrees has been shown to be useful in dynamic flight conditions.

REQUIREMENT LESSONS LEARNED (3.2.1.26)

The difficulties and risks associated with HMD development are due to the severity of the performance requirements applied and the lack of a major development effort to resolve the remaining problems. Since operational systems are still rare, it is not clear which features are essential and which could be optional.

4.2.1.26 Verification of HMD specific requirements.

TBD.

3.2.1.26.1 Sunshine video capability.

The HMD shall be capable of displaying video, with contrast, resolution, and brightness as specified herein, in a __________ ambient.

REQUIREMENT RATIONALE (3.2.1.26.1)

If a sensor is available which can "see through" certain atmospheric conditions better than the human eye, it may be useful to provide a full video capability which is bright enough to be used in sunshine. Otherwise, video is only required at night.

REQUIREMENT GUIDANCE (3.2.1.26.1)

It must be recognized that video sensors (such as FLIR) which are designed to allow vision at night will provide far less utility in sunshine. For example, the resolution of the human eye in daylight is approximately three times better than that of a 30 degree FOV FLIR, so most of the time if it is bright enough to have a sunshine legibility problem, it is bright enough to fly without the FLIR. Symbology, on the other hand, should be usable in sunshine, since this allows the HMD to be used as a HUD and HMS in daylight, just as it can at night. Viewability in sunshine is not so difficult to achieve if a dark visor is used. For example, the normal "sunglasses" visor has transmission of around 15 percent, which means that a HMD operating inside this visor would need to be visible against a 1500-fL background, rather than normal 10,000-fL sunshine.

The brightness, resolution, and contrast requirements in the HUD section of this spec can be used as a starting point.

REQUIREMENT LESSONS LEARNED (3.2.1.26.1)

4.2.1.26.1 Verification of video in sunshine capability.

TBD.

3.2.1.26.2 Image intensifier (I^2) capability.

The HMD shall include I^2 capability with the following FOV, resolution, gain, __________.

REQUIREMENT RATIONALE (3.2.1.26.2)

A capability to see in the dark can be achieved by integrating I^2 capability into the helmet. I^2s do not require use of a FLIR or helmet tracking system, therefore can result in a much less expensive system. The disadvantages are that they operate in the visible and near-IR range-therefore the crewstation lighting must be made NVG compatible-and they do not detect radiated thermal energy (as a FLIR does). They also add more weight to the helmet and complexity to the optics.

REQUIREMENT GUIDANCE (3.2.1.26.2)

Attempts have been made to design helmets with I^2 capability. Such systems must be specifically designed for use in high speed aircraft with ejection seats, with the low weight and proper center of gravity (CG) to avoid excessive stress on the pilot's neck during high-G maneuvers and the high accelerations of ejection. They must also be designed to withstand the wind blast which occurs during ejection without disintegrating and injuring the pilot.

One possibility being considered is to convert the I^2 imagery to a video signal, then display it on the HMD CRT, eliminating the need to optically combine images. This approach solves the optics weight and complexity problem, but creates the need for a camera to scan the I^2 image. This additional hardware then must be mounted on the helmet or on a gimbal controlled by the helmet position signals.

REQUIREMENTS LESSONS LEARNED (3.2.1.26.2)

4.2.1.26.2 Verification of I^2 capability.

TBD.

3.2.1.26.3 Head supported weight and center of gravity (CG).

Weight of the helmet including display hardware and ___________ feet of interconnecting cable shall not exceed ___________. CG shall be below ___________ and aft of ___________.

REQUIREMENT RATIONALE (3.2.1.26.3)

The weight of any helmet mounted equipment is critical. Any helmet becomes uncomfortable after long use, contributing to pilot performance degradation, and pilots regularly complain that their present helmet is too heavy.

REQUIREMENT GUIDANCE (3.2.1.26.3)

The actual weight which can be tolerated in a given aircraft mission must be established by human factors studies. Past studies do not provide a specific number that the display hardware can be designed to, but indicate that it depends heavily on how long it must be tolerated, in what environment, and the physical conditioning of the individuals wearing the helmet. Aircraft with a lower G requirement and no ejection seat represent a milder environment compared to a fighter. Applying the same weight and CG requirements to a HMD for these aircraft as would be applied to a fighter will most certainly drive the display hardware design to greater complexity and/or lower performance, and could only be justified on the basis of a much greater cost to support two systems in the field rather than one.

Without a firm cutoff on acceptable weight, reducing the weight to a minimum must be the goal, with the knowledge that systems such as IHADSS, at 3.9 lbs, are tolerable in helicopters. At least one study has shown that CG is at least as critical as total weight, finding that significantly more weight could be added if the CG was maintained very near or below the natural CG of the head. A high, forward CG is the worst; this fact greatly complicates the optical design of a HMD by forcing components to be mounted low and toward the back.

REQUIREMENT LESSONS LEARNED (3.2.1.26.3)

4.2.1.26.3 Verification of weight and CG.

TBD.

3.2.1.26.4 Personal equipment compatibility and interface.

The HMD shall be compatible with ___________.

REQUIREMENT RATIONALE (3.2.1.26.4)

Use of existing goggles, oxygen mask, communications gear, etc., will save substantial development effort and eliminate logistics problems associated with unique hardware being dedicated to the aircraft with the HMD. Unique personal equipment provides the possibility of improving weight and CG and optimizing interface with the display hardware.

REQUIREMENT GUIDANCE (3.2.1.26.4)

The goal, as always, should be to use the existing oxygen mask, communications gear, helmet, and nuclear/chemical/biological protective equipment if possible. However, the best solution for the overall system may be to redesign one or several of these items to improve weight, CG, or compatibility with the HMD equipment. These requirements must be established by human factors and personal equipment specialists.

REQUIREMENT LESSONS LEARNED (3.2.1.26.4)

4.2.1.26.4 Verification of compatibility with personal equipment.
TBD.

3.2.1.26.5 Compatibility with ejection seat.
TBD

4.2.1.26.5 Verification of compatibility with ejection seat.
TBD.

3.2.1.26.6 Head tracking system.
A head tracking system shall be provided which provides helmet look angle, roll angle, and position to the following accuracies: ___________. Lag time between motion of the helmet and output of angles and positions within the above tolerances shall not exceed ___________.

REQUIREMENT RATIONALE (3.2.1.26.6)

The ability of the HMD or HMS to position symbols in space, or sense where the user is pointing a helmet-mounted symbol, as well as the ability to point a head-steered sensor, depends on precise knowledge of helmet angles. Helmet position (in addition to angles) may be needed to compensate symbol positions for canopy distortions and tracker errors, and is required if pointing at closeup objects (within the cockpit) is to be used.

REQUIREMENT GUIDANCE (3.2.1.26.6)

A significant difference between early tracking systems and current systems is their ability to sense helmet roll, and therefore stabilize certain images (such as a FLIR) in roll. If an image is not "roll stabilized", the image will roll with the pilot's helmet, rather than roll with the outside scene. This can be very disorienting, giving conflicting clues as to which way is up. Without roll stabilization, if the pilot tilts his head, the FLIR scene tilts with him, rather than staying fixed in inertial space, as the outside scene does. The IHADSS system is not roll stabilized, and has been used successfully, but this appears to be more an attempt to work around equipment limitations than an actual choice. Some head position sensing systems (including the magnetic HMS) provide roll sensing with minimal increase in hardware. In the past, a complex third axis in the FLIR gimbal was required to roll-stabilize the video, but with the advent of processor-controlled scan converters and CRTs, it is now possible to electronically roll the image. If the real world scene or I^2 imagery is overlaid with FLIR video, the lack of roll stabilization of the FLIR would show up as gross misregistration between the two images. There seems to be no research showing that gross misregistration and a rotating horizon can be tolerated. Therefore head roll sensing and roll stabilization of the FLIR and symbology should be pursued.

Static accuracy of 2 mr CEP on axis, 4 mr CEP beyond 30 degrees has been recommended on some systems. Good accuracy is generally dependent on boresighting each time the system is used, to compensate for things like helmet fit.

REQUIREMENT LESSONS LEARNED (3.2.1.26.6)

A magnetically coupled head tracking system was developed several years ago and has demonstrated capability in several installations to provide sensing of the pilot's head orientation (in 3 axes) and position, with minimal weight or other encumbrance on the helmet.

4.2.1.26.6 Verification of head tracker system.

TBD.

3.2.1.26.7 Eye relief and exit pupil.

Eye relief for comfortable viewing and viewing with eyeglasses on shall be provided. Exit pupil shall be sufficient to prevent vignetting of the image with normal helmet shifting due to G loading, and shall be at least ___________ mm.

REQUIREMENT RATIONALE (3.2.1.26.7)

Adequate eye relief (distance between eyeball and optics) and exit pupil (diameter of area from which the image can be seen) are difficult to achieve in a compact, lightweight optical design, but are critical to operator performance and acceptance.

REQUIREMENT GUIDANCE (3.2.1.26.7)

Fifteen mm exit pupil has been recommended for HMDs with instantaneous or apparent FOVs up to 40 degrees. Seventeen mm has been recommended for a 45-60 degree FOV. Thirty mm of eye clearance may be needed to provide clearance for eyeglasses.

REQUIREMENT LESSONS LEARNED (3.2.1.26.7)

HMDs require compact, lightweight optics, and efficient combiners, and some require unusual optical characteristics, such as asymmetric reflectors. This appears to be an excellent area to apply diffractive optics, sometimes called holographic optics. A diffractive optics element can be thought of as a "hologram of an optical element". Instead of storing the characteristics of some object for later viewing, as is done in regular holography, the characteristics of an optical element are stored, and preserved in a thin layer of gelatin sealed between two pieces of glass. Holograms are very selective to both wavelength and angle, so they make an ideal combiner, efficiently reflecting the image from the HMD (of the right color and angle), while efficiently passing the outside scene (of random colors and angles). They are also tricky to make, with only 4 or 5 vendors in the world capable of production rates. Furthermore, their angle sensitivity can be a real problem, especially in wide field of view systems.

4.2.1.26.7 Verification of eye relief and exit pupil.

TBD.

3.2.1.26.8 Monocular/Biocular/Binocular capability.

The HMD shall provide __________ image(s), meeting the following requirements: __________.

REQUIREMENT RATIONALE (3.2.1.26.8)

The issue of whether a single image is provided to one eye ("monocular"), a single image is split and provided to both eyes ("biocular"), or an independent image is provided to each eye ("binocular") has a major effect on the performance, cost, weight, etc. of the HMD. For very wide field of view, "panoramic binocular" designs have been attempted, where the two images only overlap partially.

REQUIREMENT GUIDANCE (3.2.1.26.8)

It has been demonstrated that NVGs using two I^2 tubes ("binocular") provide better night vision than NVGs with only one tube ("monocular"). There has also been a problem with eye dominance with the IHADSS system, where the operator's brain seems to prefer to concentrate on what is seen by the unaided eye, rather than look at the FLIR image provided to one eye by the IHADSS. Viewing symbology can usually be accomplished successfully with only a monocular display. Viewing video comfortably on an HMD usually requires a biocular or binocular configuration, but the complexity of providing video to both eyes in a helmet display may be reason to reconsider. Adding a second video source, with the associated optics and alignment hardware, may increase the weight and cost of the system beyond what can be tolerated. Having two I^2 tubes can improve imagery, since the imagery reaching each eye is from an independent sensor, so the noise in the pictures is uncorrelated, and their separation provides the possibility of some depth perception due to natural parallax. On the other hand, there will only be one FLIR on board, so feeding it to both eyes provides no gain in noise cancellation or depth perception. The eye dominance problem associated with monocular systems may be the brain's natural response to receiving a dim, fuzzy, (not roll stabilized) image; it prefers to concentrate on the less confusing image from the unaided eye.

REQUIREMENT LESSONS LEARNED (3.2.1.26.8)

4.2.1.26.8 Verification of monocular/biocular/binocular capability.

TBD.

3.2.1.26.9 Peripheral vision.

The operator's unaided peripheral vision shall cover at least __________ percent of the area available with the standard __________ helmet.

REQUIREMENT RATIONALE (3.2.1.26.9)

As long as the HMD is used only as a supplement to unaided vision, the ability to see around optical structures, etc., is very important.

REQUIREMENT GUIDANCE (3.2.1.26.9)

Peripheral vision should be maintained as near to that available with a standard helmet as practical; 90 percent has been specified on one system. This is a worthy goal, but it may be an excessive driver on the design of the optics. Integration of video and symbology into the helmet should reduce the pilot's reliance on outside vision for situation awareness, and allow us to tolerate some blockage of peripheral vision if it results in a significantly better HMD capability. A design with stowable optics (optics that fold out of the way when not in use) could tolerate more blockage during use.

REQUIREMENT LESSONS LEARNED (3.2.1.26.9)

4.2.1.26.9 Verification of peripheral vision.

Verification of peripheral vision shall be by ___________.

VERIFICATION RATIONALE (4.2.1.26.9)

Verification of peripheral vision is necessary to ensure the HMD system does not adversely affect situation awareness and compromise aircrew safety during flight.

VERIFICATION GUIDANCE (4.2.1.26.9)

Consult with crew systems engineers when determining the verification procedures. Typically, verification should be accomplished by inspection of Aitoff drawings which includes a plot of the exterior vision available with the standard helmet versus the HMD helmet and by demonstration with actual hardware.

VERIFICATION LESSONS LEARNED (4.2.1.26.9)

3.2.2 Interface definition.

The equipment shall be compatible with the electrical, mechanical, and cooling interface requirements of the ___________ aircraft and the associated equipment. The equipment shall not be damaged by operation of the associated equipment when in any mode of operation (including off mode); nor shall the equipment, in any mode of operation, be damaged when any or all of the associated equipment or any unit of the ___________ is disconnected. The performance of the associated equipment shall not be degraded or interfered with by operation of the equipment covered herein.

REQUIREMENT RATIONALE (3.2.2)

It must be clear which aircraft and other systems the equipment will interface with.

REQUIREMENT GUIDANCE (3.2.2)

Names of appropriate aircraft and equipment should be filled in. Where the display equipment will interface with existing aircraft, avionics and equipment, these items should be listed specifically to insure that the manufacturer understands the interfaces and does not expect other equipment to be modified to suit him. Consult with crew systems engineers when filling in the blank for this requirement to ensure that all crew systems proposed for the aircraft are properly addressed from a compatibility viewpoint. Some interface requirements to be considered are as follows:

a) Compatibility with crew protective systems, including restraint systems, oxygen systems, anti-g systems, and all head mounted personal equipment

b) Compatibility with ejection system including the ejection sequence, ejection clearance envelope, pitot sensing system, and seat adjustment (Reference AFGS-87235).

c) Compatibility with outside visibility (Reference MIL-STD-1776).

d) Compatibility with crew station geometry and arrangement (Reference MIL-STD-1776).

REQUIREMENT LESSONS LEARNED (3.2.2)

Compatibility with the seat/escape system, flight controls, canopy and ingress/egress is often difficult to define, but drives requirements on size and layout of displays.

4.2.2 Verification of system interface.

The equipment interface shall be verified as described in the following paragraphs.

VERIFICATION RATIONALE (4.2.2)

The subparagraphs describe verification methods for each kind of interface.

VERIFICATION GUIDANCE (4.2.2)

This verification should be performed by a combination of tests and demonstrations and may be conducted together with the verifications of other requirements. Consult with crew systems engineers to determine appropriate verification procedures. Typically, compatibility with crew protective systems is verified by inspection of drawings, wind blast testing and ejection sled tests. Compatibility with the ejection system is verified by inspection of drawings, mockup evaluations, wind blast testing, and ejection sled tests. Compatibility with outside visibility is verified by inspection of Aitoff plots and actual hardware evaluation of mockups, simulation, and evaluations of the flight test article. Regardless of the number and types of tests that are performed, a full system demonstration of crew systems compatibility must be performed. During this evaluation, the crewmember should be using the full personal equipment ensemble, the equipment should be fully functional and operating and realistic simulations of the cockpit and mission procedures should be used.

VERIFICATION LESSONS LEARNED (4.2.2)

None at this time.

3.2.2.1 Electrical interface.

The equipment shall be compatible with the input signals, and provide output signals as described in ____________. Interface signals include ____________.

REQUIREMENT RATIONALE (3.2.2.1)

The numerous electrical interface signals associated with the equipment must be defined; this is often done in an Interface Control Document (ICD) which is generated as a joint effort by the display manufacturer, the system integrator or aircraft manufacturer, and the customer.

REQUIREMENT GUIDANCE (3.2.2.1)

For new systems, where the interface is not well defined, a generalized interface description or philosophy should be inserted, along with a statement of who will further define the interface. For equipment which is being retrofitted into an existing system, an ICD or equivalent document describing the existing interfaces should exist. It should be referenced and provided to bidders.

REQUIREMENT LESSONS LEARNED (3.2.2.1)

Proper documentation of all the interfaces is essential, especially when equipment is not all designed by the same team. Mistakes not only create technical problems but cause serious contractual costs and delays ("finger pointing").

4.2.2.1 Verification of electrical interface.

The presence and function of all electrical interfaces shall be verified by exercising each input and monitoring each output signal for correct response. Details of interfaces, such as tolerances, shall be verified by ___________.

VERIFICATION RATIONALE (4.2.2.1)

An exercise of all equipment functions is generally required for acceptance and in the course of this exercise one would normally expect all interfaces to be used. Specific verification of details, such as tolerances on voltages, is needed on signals which are critical or not well understood.

VERIFICATION GUIDANCE (4.2.2.1)

Acceptance tests should exercise all interfaces. One may elect to perform laboratory tests to verify interface details (such as voltage tolerances) but in most cases it is more cost-effective to wait until integration tests indicate that a problem exists and then use detail signal requirements to determine which equipment is at fault.

VERIFICATION LESSONS LEARNED (4.2.2.1)

Interaction of equipment in a System Integration Lab (SIL) environment or simulation have often produced effects which were not provided for or understood when interface control documents were developed. Where this is likely to happen, a test-and-fix approach in the SIL is the only way to reach successful interface because, even if a detailed interface test were designed and performed, it could not correct problems due to documentation oversights and mistakes.

3.2.2.1.1 Power input.

The equipment shall perform as specified herein when supplied with electrical power in accordance with the requirements of ___________ except ___________. The equipment shall remain safe, shall automatically recover to full performance, and shall remain unaffected in reliability, when exposed to transient power conditions as described in ___________. Power consumption shall not exceed ___________.

REQUIREMENT RATIONALE (3.2.2.1.1)

The electrical power available must be accurately defined, and in many cases limited, to insure compatibility.

REQUIREMENT GUIDANCE (3.2.2.1.1)

The power specification for the appropriate aircraft and any exceptions to it should be filled in. Currently, this is MIL-STD-704 for most Air Force aircraft. Maximum power consumption should be filled in if it is critical and a power budget or analysis has been performed to establish appropriate numbers. Otherwise, the blanks can be left as "To be proposed (TBP)" during the proposal phase of the program and any reasonable numbers proposed by the manufacturer filled in.

REQUIREMENT LESSONS LEARNED (3.2.2.1.1)

On some equipment it is power dissipation which is critical rather than power consumption. This is true on many displays, where limited cooling is available to the cockpit.

4.2.2.1.1 Power input.

Power input requirements shall be verified by performing an electrical power test in accordance with __________. Volt-ampere measurements shall be based on measurement of "true rms Amperes".

VERIFICATION RATIONALE (4.2.2.1.1)

A power consumption test is generally the easiest and best way to accurately determine power consumption and susceptibility to power transients.

VERIFICATION GUIDANCE (4.2.2.1.1)

Power test techniques are reasonably straightforward; a statement that a power test will be performed to verify compliance with the specified requirement should be sufficient. Testing to verify performance at voltage and frequency extremes is normally appropriate.

VERIFICATION LESSONS LEARNED (4.2.2.1.1)

Designers now use switching-mode power supplies because of their high efficiency and small size and weight. However, they can cause problems because they induce current harmonics on AC power systems. These harmonics can impose significant additional loads on generation equipment and wiring. Volt-ampere measurements must be based on measurement of "true rms Amperes", since this accurately accounts for harmonic effects.

3.2.2.1.2 Video.

The equipment shall be compatible with __________-line, __________-frame-per-second, __________-field-per-second, __________-aspect-ratio video as defined by __________. Video output for a __________ video recorder shall be provided.

REQUIREMENT RATIONALE (3.2.2.1.2)

For video displays only, video interfaces must be specified clearly.

REQUIREMENT GUIDANCE (3.2.2.1.2)

Video line rate, frame rate, aspect ratio, and the required video standard should be inserted. Many current aircraft use 525-line, 30-Hz frame, 60-Hz field, 4:3- or 1:1-aspect-ratio video similar to EIA-RS-170. Some systems use a higher voltage level (2 to 3 volts) than specified by RS-170 (1.0 or 1.5 volts) to achieve a better signal-to-noise ratio. Some systems use other line rates (mainly 875 or 1023 per EIA-RS-343) for better vertical resolution. Current systems should comply with the NATO standard (NAT-STD-3350) which allows 525-30/60, 625-25/50, and 875-30/60 line-frame/field rates and standardizes on 1.0 volt peak-to-peak. Color displays are in use on commercial aircraft which use a stroke presentation with raster fill of some symbols at a 40/80 rate. Color video should be a red-green-blue (RGB) (three-wire) signal having timing and tolerances equivalent to the monochrome signals. Some systems generating color video will also be required to generate a monochrome video output in order to allow video to be used by monochrome video recorders and backup displays. Since single-channel video recorders are in common use and quality of color video on ground playback is not critical, color video will normally be converted to NTSC or the new Y-C (Luminance-Chrominance) format for recording. New digital displays, such as Active Matrix Liquid Crystal Displays, may also use a digital fiber optics interface, such as the one used on the F-22.

REQUIREMENT LESSONS LEARNED (3.2.2.1.2)

The multitude of video formats in use has caused significant problems for displays and recorders. For example, on the F-4E PAVE TACK program, video from TISEO, radar, GBU-15, Maverick, and PAVE TACK was displayed and recorded. After the system was designed, interfaced, and flight tested, problems still occurred because the amplitudes and characteristics were different. For example, PAVE TACK FLIR video is one volt and often has large areas of gray with occasional white areas, while the radar video is three volts and often consists of large areas of black with white spots. The AGC circuit in the display could not correctly compensate for these differences, so the operator had to frequently adjust the display brightness and contrast when switching.

4.2.2.1.2 Verification of video interface.

Compatibility with the specified video interface shall be demonstrated by ___________.

VERIFICATION RATIONALE (4.2.2.1.2)

Video interfaces must be tested or demonstrated to assure compatibility.

VERIFICATION GUIDANCE (4.2.2.1.2)

The video signal voltage and timing characteristics can be measured if deemed necessary, but it is sometimes adequate to rely on (a) laboratory demonstrations of compatibility with standard video generation equipment, and (b) integration laboratory or aircraft demonstration of system compatibility.

VERIFICATION LESSONS LEARNED (4.2.2.1.2)

3.2.2.1.3 Data bus.

The equipment shall interface with the ___________ data bus.

REQUIREMENT RATIONALE (3.1.2.1.3)

For equipment on aircraft which have a data bus, use of the bus and characteristics of the bus must be specified.

REQUIREMENT GUIDANCE (3.1.2.1.3)

To simplify and standardize interfaces, it is desirable to make maximum practical use of standard bus interfaces, such as the MIL-STD-1553B, Notice 2, multiplex bus, or the ARINC 429 or 629 buses. System considerations such as bus loading and the amount and type of data to be interfaced will indicate which units should operate on the data bus, how many busses are needed, and which units should be bus controllers. This can range from putting each unit of a display system on the bus to putting only one electronics unit/symbol generator on the bus.

REQUIREMENT LESSONS LEARNED (3.1.2.1.3)

Unique data busses, such as were originally used on the F-15 and F-111, reduce other application possibilities for the equipment and increase life cycle cost.

4.2.2.1.3 Verification of data bus.

Compatibility with the specified data bus interface shall be verified by ___________.

VERIFICATION RATIONALE (4.2.2.1.3)

Bus interfaces must be tested or demonstrated to assure compatibility.

VERIFICATION GUIDANCE (4.2.2.1.3)

All new and modified designs must be tested to insure compatibility with required interfaces. Any hardware or software changes made in a unit may inadvertently make it non compliant with the standard. MIL-HDBK-1553 provides extensive guidance on the design and application of MIL-STD-1553.

The failure to conduct thorough compliance tests on individual units prior to systems integration results in lengthened integration and flight test activities, slipped schedules, and high costs for design/construction error correction. In addition, future system growth options may be closed off due to noncompliance problems which are too costly to correct; or worse yet, problems may remain undetected until the future modifications are attempted.

VERIFICATION LESSONS LEARNED (4.2.2.1.3)

3.2.2.2 Mechanical interface.

The equipment shall be designed to be ___________ mounted. Mounting interface details and tolerances shall be in accordance with ___________.

REQUIREMENT RATIONALE (3.2.2.2)

Mechanical interface must be defined to assure compatibility.

REQUIREMENT GUIDANCE (3.2.2.2)

Any mounting details which are known should be inserted. "Hard" mounting (no shock mounts) is generally required for avionics units which can be designed to tolerate the vibration and shock environment. An outline dimensional drawing or reference to a mechanical interface control document should be inserted.

Certain instrument sizes and mounting configurations have become standardized through multiple usage. ARINC A, B, C, and D size are considered as standard in commercial airliners and are used in some military aircraft. Equipment-bay-mounted units often use ARINC-ATR-style, quick-disconnect mounts which facilitate replacement of the equipment.

REQUIREMENT LESSONS LEARNED (3.2.2.2)

4.2.2.2 Verification of mechanical interface.

Inspection and ___________ shall be used to verify compliance.

VERIFICATION RATIONALE (4.2.2.2)

Interface must be verified by analysis and demonstration for installation and interchangeability of units in the aircraft.

VERIFICATION GUIDANCE (4.2.2.2)

A dimensional tolerance analysis comparing the two sides of the interface may be required for complicated or precision interfaces. System integration and flight tests are the ultimate test of the interface and are often adequate by themselves to verify compliance.

VERIFICATION LESSONS LEARNED (4.2.2.2)

3.2.2.3 Cooling.

The equipment shall be cooled by ___________.

REQUIREMENT RATIONALE (3.2.2.3)

Cooling method must be established.

REQUIREMENT GUIDANCE (3.2.2.3)

Free convection cooling is preferred where low dissipation and adequate ambient air make it practical. When forced air cooling is available, better reliability and lower equipment cost can generally be achieved by using it, and information on temperature, pressure, flow rate, interface hardware and contamination limits should be inserted in the specification. Use of internal fans or conductive heat transfer to the mounting base is also appropriate in some situations. In the past, military standards prohibited blowing ambient air over electronics components, so most military avionics which use cooling air are "cold plate" designs, i.e., have a plenum and heat exchanger to remove heat from the edges of circuit boards without allowing cooling air to contact (and contaminate) circuitry.

REQUIREMENTS LESSONS LEARNED (3.2.2.3)

Some equipment also has a requirement to operate for a specified period without cooling.

4.2.2.3 Verification of cooling.

Compliance with the cooling requirements shall be verified by __________.

VERIFICATION RATIONALE (4.2.2.3)

Compliance with cooling requirements must be verified, usually by test.

VERIFICATION GUIDANCE (4.2.2.3)

Cooling provisions should be simulated during temperature-altitude tests. Separate cooling air tests are generally performed on forced-air-cooled equipment to measure flow rate, pressure drop, and susceptibility to dirt and water contamination.

It is important to account for any special cooling apparatus in tests demonstrating compliance with cooling requirements. If the display needs a fan, for example, to meet the cooling requirements, it is important that all acceptance tests be run with the fan in operation and that any fan failures be counted as relevant failures.

VERIFICATION LESSONS LEARNED (4.2.2.3)

Cooling fans can create excessive noise in the cockpit. Permissible noise levels must be specified and tested if use of fans is anticipated.

3.2.2.4 Display recording interface.

The equipment shall provide the following interface for cockpit TV video recording: __________.

REQUIREMENT RATIONALE (3.2.2.4)

Most HUDs must interface with a cockpit TV camera to provide a recording capability. Recordings are used in training, target damage assessment, and in locating system problems which may be impossible to duplicate on the ground.

REQUIREMENT GUIDANCE (3.2.2.4)

A Cockpit TV System (CTVS) (miniature video camera) is currently used in most Air Force fighter aircraft. Most HUDs provide a CTVS mounting surface which must be specified. For a HUD using conventional refractive optics, the CTVS is mounted aft of the combiner where it "sees" all HUD symbology as well as the outside scene. In HUDs which use a diffraction (holographic) optics combiner, the CTVS is mounted forward of the combiner and the symbology is electronically overlaid. Many systems also provide composite video outputs of sensor video and/or display symbology to a video tape recorder. The user's needs, in terms of which displays are to be recorded, and the quality/accuracy to be achieved, should be inserted. A hand-held video camera has also been considered on at least one aircraft.

REQUIREMENT LESSONS LEARNED (3.2.2.4)

4.2.2.4 Verification of display recording interface.

Compliance shall be verified by __________.

VERIFICATION RATIONALE (4.2.2.4)

Proper camera interface must be verified to assure adequate video recording.

VERIFICATION GUIDANCE (4.2.2.4)

Mechanical or electrical tests or inspections should be specified, depending on the type of interface.

VERIFICATION LESSONS LEARNED (4.2.2.4)

3.2.3 Product integrity.

The equipment shall perform within specifications for a service life of ___________ years when subjected to the environments which are expected to occur during the intended usage. The equipment shall perform within specifications after exposure to the expected transportation, manufacture, storage, and maintenance environments. Other product integrity requirements shall be established in accordance with MIL-HDBK-87244.

REQUIREMENT RATIONALE (3.2.3)

A formal product integrity program reduces development and life cycle problems with electronic systems which must withstand the often severe environment within aircraft and perform under adverse conditions. It integrates the numerous plans, analyses, and tests and ensures that the required activities are completed at the correct time to influence the design and manufacture of the product. The length of time the equipment will be used will affect many aspects of the design.

The following discussion deals mainly with those aspects of integrity that are unique to displays - this information should be integrated with an overall avionics integrity program.

REQUIREMENT GUIDANCE (3.2.3)

The actual environment will depend on the aircraft type and mission. Environments for transportation, storage, maintenance, etc., must be assessed to determine if they are less severe than the operational environments and considered in the design if they consume a significant part of the life. Refer to MIL-HDBK-87244 for further guidance.

A structured and disciplined engineering approach is necessary to ensure electronics will perform their function reliably for their intended service life is required. Early in the design phase, engineers should develop a thorough understanding of how the electronics will be used (design usage) as well as the environments the electronics will be exposed to and operated in. This understanding helps designers/engineers determine various stresses the electronics will experience during the service life cycle. It is also necessary to understand the properties, characteristics, and variabilities of materials, parts, and processes used in the equipment. This knowledge and data are then used to analyze and evaluate the durability and damage tolerance of the equipment. These analyses are supported and supplemented by appropriate engineering/development tests. Incremental verification of the durability and service life requirements takes place via analyses, lower level engineering tests, and finally a Durability Life Test (DLT). Appropriate life management and quality assurance provisions are established.

Environments will typically be much different for cockpit-mounted units than for equipment-bay-mounted units. For example, temperatures over 100°C have been measured in a closed, non-operating cockpit under desert conditions.

A Sunshine and Ultraviolet Radiation requirement applies to cockpit equipment which will be exposed to sunshine, either while operating or non-operating. An intensity of 950 W/m^2 (88 W/ft^2) has been used to represent a closed cockpit in the desert. Radiation of 1076 W/m^2 (100 W/ft^2) is appropriate for a canopy-open condition, but should not be used with the maximum closed cockpit temperature. Most long term damage is due to ultraviolet radiation; a test using 5000 hours of UV radiation at 100 W/m^2 has been used to simulate a lifetime of UV exposure. Organic dyes and materials tend to be most susceptible.

Display equipment must be designed to prevent entrapment of fluids, such as rain, and must not be damaged by contact with oil, fuel, or de-icing fluid. Optical filters are generally affected by oil (including oily fingerprints), and must return to full performance when washed with alcohol or window washing detergent.

Requirements for resistance to contact with fluids should not be applied to items where meeting them is impractical or of little value. For example, the tape used in video tape recorders is generally not usable after contact with these fluids, but it is expendable and it is not practical to make cassettes watertight.

Full performance in some extreme environments is sometimes not required, for example:

a) Flicker, jitter, noise, resolution, etc. of a display may be allowed to deviate from specifications during gunfire, provided the picture remains usable, since the vibration is severe and the duration is short.

b) A magnetic field environment of up to 5 Gauss, with a gradient of up to 6 Gauss per ft (20 Gauss per meter) is sometimes applied. High resolution color CRTs may lose color purity under these conditions. A deviation should be allowed in this case, since these are short-term, worst-case conditions, normal operating conditions are much less severe, the image remains usable, and preventing the purity loss would require other design compromises.

c) Many avionics displays require full performance within two-minutes of startup at cold temperatures (-40°C or -54°C). Displays required for engine starting and emergency taxiing in aircraft that must start quickly on alert will have shorter startup times. It is often appropriate to allow deviations from full performance (reduced brightness, distortion, smearing, image lag) for the first five or ten minutes, since such cold starts should be rare, the displays would still be usable, and meeting full performance may require other compromises, such as use of excessive heater power.

The traditional documents on standard environmental requirements and environmental test methods (MIL-STD-461, RTCA-DO-160 and the MIL-STD with an '8', a '1' and a '0' in the number--which we are no longer allowed to reference) may provide additional guidance on general levels and test methods that are in common use, but the specific environments of the equipment in question should be the overriding factor.

A CRT life requirement is often included for high brightness CRT displays such as a HUD, where the CRT is typically driven very hard in order to meet brightness requirements. A duration and brightness which represents the normal amount of operation at full brightness should be used. One thousand hours at 6,800 cd/m^2 (2,000 fL) measured off the combiner was specified for the LANTIRN HUD CRT. ASC/ENAS tested a similar CRT at 38,000 cd/m^2 (11,000 fL) measured at the CRT (no filters) and found that its life was significantly shortened.

Electromechanical elapsed time indicators were once used in most display units, but they added cost and failure modes to the equipment. Modern equipment with a processor and non-volatile memory can electronically record operating time, on/off cycles, flying time, etc., with very little additional hardware.

REQUIREMENT LESSONS LEARNED (3.2.3)

The rain, high humidity and high temperature environment has been observed at Eglin AFB, where F-4 canopies left open during maintenance were closed as quickly as practical during a sudden summer thunderstorm. After the storm, maintenance operation continued, with sunshine heating up the closed, wet cockpit.

The anti reflective coating on the F-16 radar display experienced excessive spotting after only 25 hours of a severe humidity test. The requirement for this filter was changed to a less severe requirement, since it could meet this requirement and the filter is in a position where it will dry quickly.

4.2.3 Verification of product integrity.

Verification shall be by ___________.

VERIFICATION RATIONALE (4.2.3)

Compliance must be verified to assure that the equipment withstands the environment and has adequate service life and durability characteristics.

VERIFICATION GUIDANCE (4.2.3)

Tests, analyses, demonstrations, and inspections, as outlined in MIL-HDBK-87244, should be used.

Equipment using forced-air cooling should be subjected to a "sand and dust in the cooling air" test if small or complex air passages are used, or if the cooling air passes over components or connectors.

Verification of fungus resistance is often done by analysis on avionics, since modern electronic equipment usually contains very little fungus nutrient material.

VERIFICATION LESSONS LEARNED (4.2.3)

Significant degradation of display optical filters in sunshine has been experienced. As a result of field degradation of filters on F-4 Wild Weasel aircraft, filter tests were performed and certain laminated filters were found to degrade. Holographic optical elements from the LANTIRN HUD program were also tested for approximately 900 hours at 150 W/m^2, which was intended to represent three years of sunshine. These elements contain a layer of dichromated gelatin, and the test result showed minimal degradation.

3.2.4 Maintainability.

The design of the equipment shall be such that the unscheduled active corrective maintenance times at the organizational and intermediate levels shall not exceed the following:

[a] Mean corrective maintenance time: Organizational level: ___________ hours Intermediate level: ___________ hours

[b] Maximum corrective maintenance time (95th percentile): Organizational level: ___________ hours Intermediate level: ___________ hours

REQUIREMENT RATIONALE (3.2.4)

Design for maintainability is a critical driver of life cycle cost.

REQUIREMENT GUIDANCE (3.2.4)

Maintenance times should be specified based on an analysis of equipment complexity, deployment concept, and maintenance time budget. This can be a very subjective area, and the actual requirement inserted in the specification may be based on the opinion of an engineer who has experience on recent maintainability demonstrations of similar equipment. The times specified should be short enough to require good design practice and encourage innovative approaches to easy maintenance, but long enough to allow reasonable performance, reliability, and cost.

REQUIREMENTS LESSONS LEARNED (3.2.4)

4.2.4 Maintainability verification.

Maintainability demonstration testing shall be conducted in accordance with ___________, to demonstrate that the maintainability requirements specified herein have been satisfied. The conditions of the maintainability demonstration and tasks demonstrated shall represent those which can be expected to occur in the operational environment. Task selection shall be in accordance with ___________. A single simulated or induced fault or failure may be counted as a maintenance action at both the organizational and intermediate levels when practical.

VERIFICATION RATIONALE (4.2.4)

For development programs where the designer has some control over the maintainability features of the equipment, a demonstration is needed to assure equipment availability and maintenance costs will be acceptable.

VERIFICATION GUIDANCE (4.2.4)

A maintainability demonstration may be done in the Engineering/Manufacturing Development phase.

VERIFICATION LESSONS LEARNED (4.2.4)

3.2.4.1 Maintenance concept.

The equipment shall be designed for a ___________ maintenance concept. This maintenance concept consists of ___________.

REQUIREMENT RATIONALE (3.2.4.1)

In many cases the maintenance concept for a piece of equipment should be specified to assure that it will be compatible with existing spares provisioning and maintenance procedures.

REQUIREMENT GUIDANCE (3.2.4.1)

The three-level (organizational, intermediate, and depot) maintenance concept has been used in the past for most complex electronic units, such as CRT displays. This philosophy should be reevaluated for new technology and packaging schemes. For example, a small circuit card or a hermetically sealed module may be cheaper to maintain as a throw-away module (no depot repair) rather than buy spare parts, data, and support equipment to repair it. A description of planned basing and shop mobility requirements should also be included, if possible, to guide decisions on how each part should be maintained.

REQUIREMENT LESSONS LEARNED (3.2.4.1)

The trend toward better built-in-test (BIT), and the high cost of providing intermediate support facilities at remote locations, have caused most programs to change to a two-level maintenance concept. Under this concept, problems are isolated to the failed module or assembly on the aircraft, based on BIT, and failed modules are shipped directly to a depot for repair.

4.2.4.1 Verification of maintenance concept.

Compliance shall be verified by analysis.

VERIFICATION RATIONALE (4.2.4.1)

Use of design philosophy for the chosen maintenance concept must be verified to assure low maintenance cost.

VERIFICATION GUIDANCE (4.2.4.1)

Analysis of documentation can be used to verify compliance.

VERIFICATION LESSONS LEARNED (4.2.4.1)

3.2.4.2 Scheduled maintenance.

The equipment shall be designed to minimize scheduled preventive maintenance. Scheduled preventive maintenance shall not be allowed for any parts replacement unless it is established that such parts have a wearout characteristic which results in a determinable life span with non-random life distribution characteristics.

REQUIREMENT RATIONALE (3.2.4.2)

Scheduled maintenance is generally prohibited for electronic display equipment because of the cost in time and paperwork required to plan and perform it and keep the corresponding records.

REQUIREMENT GUIDANCE (3.2.4.2)

Scheduled preventive maintenance is normally not allowed.

REQUIREMENT LESSONS LEARNED (3.2.4.2)

4.2.4.2 Scheduled maintenance.

Compliance shall be verified by audit of maintenance data.

VERIFICATION RATIONALE (4.2.4.2)

Compliance must be verified to assure that the equipment is easily maintainable.

VERIFICATION GUIDANCE (4.2.4.2)

The fact that no scheduled maintenance is included in the maintenance manuals, or reliability analysis and test, must be verified to assure low cost field operation.

VERIFICATION LESSONS LEARNED (4.2.4.2)

3.2.4.3 Self tests.

The equipment shall have the capability to display and/or report faults and out-of-tolerance conditions by employing an automatic, non-interruptive self-test. Self tests shall be capable of detecting __________ percent of all faults. Self test false alarms shall not exceed __________ percent of indicated faults. Faults or out-of-tolerance conditions that are obvious by looking at the display are considered "detected" even if they are not electronically reported.

REQUIREMENT RATIONALE (3.2.4.3)

Equipment self test is easily implemented on digital equipment, and generally provides confidence that equipment is working properly. Analog circuitry (such as that driving a CRT) is harder to test.

REQUIREMENT GUIDANCE (3.2.4.3)

For mission-essential equipment containing a digital processor, a high level of mission-essential fault detection and a low false alarm rate should be specified. A ninety-five percent detection and a one percent false alarm rate is not uncommon.

REQUIREMENT LESSONS LEARNED (3.2.4.3)

4.2.4.3 Verification of self tests.

Compliance shall be verified by __________.

VERIFICATION RATIONALE (4.2.4.3)

Appropriate detection and false alarm rates must be verified to assure that the equipment user will have confidence in the equipment and insure that he does not unknowingly rely on degraded equipment.

VERIFICATION GUIDANCE (4.2.4.3)

Data gathered during a maintainability demonstration is generally adequate to be used in an analysis to verify this requirement.

VERIFICATION LESSONS LEARNED (4.2.4.3)

3.2.4.4 Built-in tests (BIT).

Operator-initiated BIT, supplemented by self test, shall be capable of detecting at least ___________ percent of the malfunctions and out-of-tolerance conditions (at their predicted frequencies) with a false alarm rate of less than ___________ percent. BIT, supplemented as necessary by self test, shall be capable of isolating to the faulty LRU a minimum of ___________ percent of the detected malfunctions and out-of-tolerance conditions. The BIT shall isolate to the faulty SRU ___________ percent of the time. Built-in tests may require interruption of normal equipment operation. If applicable, selection of the BIT shall result in the equipment self generation and display of the appropriate test pattern on the display surface. BIT results shall be easily interpretable without the use of table lookups. Faults or out-of-tolerance conditions that are obvious by looking at the display are considered "detected" even if they are not electronically reported.

REQUIREMENT RATIONALE (3.2.4.4)

A BIT capability generally does away with organizational level (on-aircraft) test equipment and allows for the fastest possible correction of problems on the aircraft.

REQUIREMENT GUIDANCE (3.2.4.4)

High levels of fault detection and isolation to the faulty LRU are important in reducing unnecessary LRU replacements and improving aircraft availability. A ninety-five percent detection, ninety percent isolation, and five percent false alarm rate can be achieved in new equipment which is mostly digital, and processor-controlled. Isolation to the faulty SRU is also required in some cases. The system specification for the KC-135 ICDU required the following SRU fault isolation performance:

90 percent to one SRU

95 percent to two SRUs

100 percent to three SRUs

Some display parameters are best evaluated by operator interpretation of an internally generated BIT pattern display. A flightline go/no-go evaluation of brightness, contrast, resolution, color convergence, and purity (on shadow mask CRTs), etc., based on an internally generated test image should be considered.

REQUIREMENT LESSONS LEARNED (3.2.4.4)

A test pattern generated within the display system helps maintenance personnel quickly decide whether the display, or a system providing data to the display, is at fault.

4.2.4.4 Verification of built in tests.

The BIT capability shall be verified by analysis and by data gathered during the maintainability demonstration test and flight tests.

VERIFICATION RATIONALE (4.2.4.4)

BIT capability must be verified to assure low maintenance costs and high aircraft availability rates.

VERIFICATION GUIDANCE (4.2.4.4)

Verification should be based on data collected during maintainability and flight test.

VERIFICATION LESSONS LEARNED (4.2.4.4)

3.2.4.5 Testability.

Each LRU shall contain test points in accordance with __________. Each SRU shall have test access points in accordance with __________. These test points shall be adequate to allow the following levels of fault detection:

[a] The minimum acceptable level of fault detection shall be __________ percent of all failures of digital SRUs and __________ percent for analog SRUs.

[b] Fault isolation to a single circuit element (component) in __________ percent of the detected failures for digital SRUs and __________ percent to three active components on analog SRUs.

REQUIREMENT RATIONALE (3.2.4.5)

Design for testability is needed to assure that maintenance work and support equipment is reasonably simple.

REQUIREMENT GUIDANCE (3.2.4.5)

These requirements are dependent upon the type of equipment and the maintenance concept chosen and should be established by a thorough analysis of these factors. Fault detection rates of 90 percent (sometimes 95 percent or 99 percent) for digital SRUs and 90 percent for analog SRUs have been used. Isolation to a single component in 90 percent of failures on digital SRUs, and to three components on 90 percent of analog failures, has been used.

REQUIREMENT LESSONS LEARNED (3.2.4.5)

4.2.4.5 Verification of testability.

Testability design shall be verified by use of analytical/statistical data prepared either manually or by making use of available computer aided test analysis programs such as the Navy/Air Force Logic Stimuli and Response (LASAR) program.

VERIFICATION RATIONALE (4.2.4.5)

Testability must be verified to assure that equipment is easily repairable.

VERIFICATION GUIDANCE (4.2.4.5)

Verification is normally done by analysis.

VERIFICATION LESSONS LEARNED (4.2.4.5)

3.2.4.6 Fault reporting.

The equipment shall report self test- and BIT-detected faults to the __________ via the data bus.

REQUIREMENT RATIONALE (3.2.4.6)

For aircraft having a central computer capable of storing maintenance data, self test- and BIT-detected failures should be reported in order to allow rapid maintenance. This is particularly important in finding faults which are intermittent or only occur in certain flight conditions.

REQUIREMENT GUIDANCE (3.2.4.6)

This requirement should be applied wherever a computer capable of storing fault data is available. In a system with no central fault reporting system, the display subsystem should record a history of its fault reports. This data should be retained in a non-volatile memory until it is intentionally cleared by a maintenance person.

REQUIREMENT LESSONS LEARNED (3.2.4.6)

4.2.4.6 Verification of fault reporting.

Compliance shall be verified by __________.

VERIFICATION RATIONALE (4.2.4.6)

Verification is needed to assure that faults reported to the computer are consistent with what the operator saw.

VERIFICATION GUIDANCE (4.2.4.6)

Data can be taken during the maintainability demonstration to analyze compliance.

VERIFICATION LESSONS LEARNED (4.2.4.6)

3.2.5 Weight.

The weight of the equipment shall be kept to a minimum. The weight shall not exceed __________.

REQUIREMENT RATIONALE (3.2.5)

Weight of equipment should be specified to prevent adding excessive weight to the aircraft, and in many cases to meet critical aircraft weight and balance requirements.

REQUIREMENT GUIDANCE (3.2.5)

Equipment designed for retrofit into existing aircraft may have to meet specific existing limits. For new aircraft, the manufacturer should allocate allowable weights to the various avionics or provide specific guidance on the severity of weight control measures to be taken.

REQUIREMENT LESSONS LEARNED (3.2.5)

4.2.5 Verification of weight.

The equipment shall be weighed.

VERIFICATION RATIONALE (4.2.5)

Weight must be measured to assure that excessive weight is not added to the aircraft.

VERIFICATION GUIDANCE (4.2.5)

Equipment shall be weighed.

VERIFICATION LESSONS LEARNED (4.2.5)

3.2.6 Volume.

The equipment shall not exceed the volume of ___________.

REQUIREMENT RATIONALE (3.2.6)

Volume must be constrained to fit in the available aircraft space.

REQUIREMENT GUIDANCE (3.2.6)

Equipment designed for retrofit into existing aircraft must generally fit into an existing space, whose dimensions can be obtained from existing design data and put in the specification in the form of dimensions or a sketch (figure) showing the outline.

REQUIREMENT LESSONS LEARNED (3.2.6)

4.2.6 Verification of volume.

The dimensions of the equipment shall be measured.

VERIFICATION RATIONALE (4.2.6)

Volume must be measured to assure that equipment will fit.

VERIFICATION GUIDANCE (4.2.6)

Verification should be by measurement.

VERIFICATION LESSONS LEARNED (4.2.6)

3.3 Design and construction.

4.3 Verification of design and construction.

3.3.1 Explosive decompression.

The ___________ shall not be damaged and shall perform as specified after an explosive decompression of the surrounding air. The pressure change shall be ___________.

REQUIREMENT RATIONALE (3.3.1)

Crewstation equipment should survive a sudden decompression caused by battle damage, canopy removal, etc.

REQUIREMENT GUIDANCE (3.3.1)

Equipment located in the crewstation may be exposed to explosive decompression and should continue to operate. An appropriate air pressure change rate and limits must be inserted.

REQUIREMENT LESSONS LEARNED (3.3.1)

This requirement is not applied to all crewstation equipment but should be applied to any equipment in a pressurized area which is critical to safety.

4.3.1 Verification of explosive decompression.

Crewstation equipment shall be subjected to an explosive decompression test or analysis. The initial altitude shall be __________ and the final altitude __________. The rate of change of pressure shall be at least __________.

VERIFICATION RATIONALE (4.3.1)

Compliance must be verified to assure operation of equipment after decompression.

VERIFICATION GUIDANCE (4.3.1)

The cabin altitude and flight altitude corresponding to the greatest pressure change should be inserted.

VERIFICATION LESSONS LEARNED (4.3.1)

3.3.2 Safety.

The equipment shall incorporate design features in accordance with __________ which promote the health and safety of those personnel who will use and maintain the system. Hazards which may cause adverse explosive, fire, mechanical, or biological effects on personnel during system operation, test, maintenance, and training shall be eliminated or controlled.

REQUIREMENT RATIONALE (3.3.2)

Safety requirements and features are needed to protect personnel and equipment.

REQUIREMENT GUIDANCE (3.3.2)

Hazards associated with displays include:

a) Exposure to mercury. Florescent tubes used as backlights for AMLCDs contain a small amount of mercury. This has been evaluated and determined to pose no more threat (in the rare instance that a bulb would break in the cockpit or during maintenance) than the florescent tubes used in office and residential lighting. The amount of mercury in a florescent tube is so small that no extra precautions are normally taken.

b) Implosion of CRTs. The CRT is a large glass vacuum tube, and will implode violently if broken. The pilot should be protected from flying glass by a filter glass bonded to the front of the CRT, which effectively makes the faceplate much stronger than the rest of the CRT, so the glass will be contained within the display unit box.

c) LCD fluid. The liquid crystal fluid inside an AMLCD could escape if the glass were broken. The amount of this fluid in a display (a layer of only 5-8 microns thick) is too small to be a hazard.

d) Broken glass from an AMLCD. The front glass on an LCD is generally thin (compared to CRT faceplates). If it is impacted by a tool, a person's foot, etc., it could break, exposing the crew to sharp glass fragments. This is not particularly significant in a normal cockpit environment, but in a zero-gravity environment the broken glass fragments are a hazard because they can be inhaled or ingested. This has resulted in a requirement for a rugged faceplate, tested by the "steel ball drop test" for displays used in space applications.

REQUIREMENT LESSONS LEARNED (3.3.2)

4.3.2 Verification of safety.

The equipment shall be inspected to determine compliance.

VERIFICATION RATIONALE (4.3.2)

Compliance must be verified to assure that personnel are not exposed to unnecessary hazards.

VERIFICATION GUIDANCE (4.3.2)

Verification should be done by inspection.

VERIFICATION LESSONS LEARNED (4.3.2)

3.3.2.1 Escape clearance.

The design of cockpit/crewstation equipment shall be compatible with the escape envelope and ingress/egress requirements as described by ____________. Final escape envelope clearance shall be approved by the procuring activity.

REQUIREMENT RATIONALE (3.3.2.1)

For equipment located near the ejection envelope of an aircraft with ejection seats, clearance must be provided for safety.

REQUIREMENT GUIDANCE (3.3.2.1)

Drawings or other data showing required clearance for cockpit equipment should be provided, usually as a figure in the specification.

REQUIREMENT LESSONS LEARNED (3.3.2.1)

4.3.2.1 Verification of escape clearance.

Escape clearance shall be verified by __________.

VERIFICATION RATIONALE (4.3.2.1)

Escape clearance must be verified to assure safety.

VERIFICATION GUIDANCE (4.3.2.1)

Drawing analysis or a cockpit/crewstation demonstration should be used, depending on the equipment's position in the cockpit. AFGS-87235 covers additional escape system requirements.

VERIFICATION LESSONS LEARNED (4.3.2.1)

3.3.2.2 Acoustic noise generation.

Cockpit equipment shall not generate noise in excess of __________ dB.

REQUIREMENT RATIONALE (3.3.6.2)

Cockpit noise level must not be high enough to interfere with pilot or maintenance personnel performance.

REQUIREMENT GUIDANCE (3.3.6.2)

Noise levels should not exceed 75 dB where this can be easily achieved. Acceptable levels of equipment noise will depend on the duration of exposure and sound attenuation characteristics of helmets and other personal equipment.

REQUIREMENT LESSONS LEARNED (3.3.6.2)

Noise from avionics is generally caused by high speed cooling fans. In some cases, noise created by equipment bay units is also a problem since maintenance personnel must be able to converse while performing bench checkout.

4.3.2.2 Verification of acoustic noise generation.

Personnel exposure protection from acoustic noise shall be verified on the A scale of a standard sound level meter at slow response. If the alternate octave band analysis method is used, the equivalent A-weighted sound level may be determined from __________. This test may be waived if the equipment does not produce significant noise.

VERIFICATION RATIONALE (4.3.2.2)

Compliance must be verified to assure noise is not objectionable.

VERIFICATION GUIDANCE (4.3.2.2)

Compliance should be verified by test unless the equipment does not produce significant noise. The equivalent A-weighted sound level may be determined from AFR 151-35.

VERIFICATION LESSONS LEARNED (4.3.2.2)

3.3.2.3 X-ray emissions.

The equipment shall not produce x-ray emissions of more than __________ milliroentgen per hour under normal operating conditions.

REQUIREMENT RATIONALE (3.3.2.3)

REQUIREMENT GUIDANCE (3.3.2.3)

The high voltage accelerated electron beam of a CRT can produce dangerous x-rays, especially in high-brightness color designs with anode voltage over 30 kV. A limit of one milliroentgen per hour has been used. Reference OSHA, Code of Federal Regulations, part 1910.

REQUIREMENT LESSONS LEARNED (3.3.2.3)

4.3.2.3 Verification of x-ray emissions.

TBD

3.3.2.4 Crash safety.

The cockpit equipment shall withstand the crash safety shock of __________. The equipment shall remain in place without failure of the mounting attachment and shall not create a hazard; bending and distortion are permitted.

REQUIREMENT RATIONALE (3.3.2.4)

Equipment must not create a hazard to the crew in case of a crash landing.

REQUIREMENT GUIDANCE (3.3.2.4)

Appropriate crash safety shock levels for the intended aircraft should be inserted. The requirement should be applied to crewstation equipment only.

REQUIREMENT LESSONS LEARNED (3.3.2.4)

4.3.2.4 Verification of crash safety.

Cockpit equipment shall be subjected to the crash safety test as described in __________.

VERIFICATION RATIONALE (4.3.2.4)

Compliance must be verified by test or analysis for safety.

VERIFICATION GUIDANCE (4.3.2.4)

A test on a structural mockup or an analysis of design data is often an appropriate alternative to a test of actual equipment, since the g levels are very high and can damage valuable equipment.

VERIFICATION LESSONS LEARNED (4.3.2.4)

3.3.2.5 Combining glass bird strike.

The canopy is such that it can deflect and impact the HUD combiner when bird strike occurs. Therefore, the HUD combiner and its mounting shall be designed to prevent large, sharp, or high velocity fragments from disabling the pilot when the combiner is struck along its upper edge.

REQUIREMENT RATIONALE (3.3.2.5)

In some aircraft, the HUD combiner glass is close to the canopy and the canopy can deflect sufficiently under bird strike conditions to impact the combiner. While it is preferred to make the canopy more rigid and/or higher to provide clearance, weight and aerodynamics considerations have made this impractical in several fighter aircraft. In these cases, the HUD was designed to withstand the shock of a bird strike on the canopy without injuring the pilot.

REQUIREMENT GUIDANCE (3.3.2.5)

This paragraph should be deleted, except for a HUD in an aircraft with a canopy that can deflect and impact the HUD. Data on aircraft type, airspeed, and canopy configuration should be inserted.

REQUIREMENT LESSONS LEARNED (3.3.2.5)

4.3.2.5 Verification of combining glass bird strike.

The combining glass, along with a windscreen mounted in the aircraft configuration, shall be subjected to a bird strike test in accordance with ____________.

VERIFICATION RATIONALE (4.3.2.5)

Compliance must be verified to assure pilot safety.

VERIFICATION GUIDANCE (4.3.2.5)

A bird strike test, such as the one performed by General Dynamics on the F-16 HUDs, is generally appropriate.

VERIFICATION LESSONS LEARNED

3.3.3 Human engineering.

4.3.3 Human engineering verification.

3.3.3.1 Handles and grasp areas.
Handles and grasp areas, for ease of handling and installation, shall be provided in accordance with ____________.

REQUIREMENT RATIONALE (3.3.3.1)

Equipment must be designed for compatibility with human operators to be useful.

REQUIREMENT GUIDANCE (3.3.3.1)

Extensive guidance is contained in MIL-STD-1472.

REQUIREMENT LESSONS LEARNED (3.3.3.1)

4.3.3.1 Verification of handles and grasp areas.
The equipment shall be inspected to determine compliance.

VERIFICATION RATIONALE (4.3.3.1)

Verification is required to assure comfortable and safe equipment handling.

VERIFICATION GUIDANCE (4.3.3.1)

Verification shall be done by inspection.

VERIFICATION LESSONS LEARNED (4.3.3.1)

3.3.3.2 Keyboard requirements.
[a] Key travel and pressure. The operating travel for the keys shall be ____________. The operating pressure shall be ____________. Key operation shall provide tactile feedback such that an operator wearing gloves can clearly tell when a key is actuated.

[b] Key operation. All keys shall operate in a ____________ mode.

[c] Key size and spacing. The keys shall be ____________ and shall be no closer than ____________ edge to edge from any other key, switch, or knob.

REQUIREMENT RATIONALE (3.3.3.2)

For equipment with a keyboard, the characteristics of the keyboard must be specified to assure that comfortable, accurate operation in the airborne environment is possible. These requirements will also apply to push buttons, such as might be located on the periphery of an MFD.

REQUIREMENT GUIDANCE (3.3.3.2)

The operator should receive positive tactile feedback that a key has indeed been activated; however, it is important that the operating pressure be such that keys are not easily activated by accident. The KC-135 ICU key operating pressure was originally specified at 16 ±4 ounces but was later changed to 20 ±4 ounces. The operating travel was specified to be 0.13 to 0.51 cm (0.05 to 0.20 inch) with clear tactile feedback.

4.3.3.2 Verification of keyboard requirements.

The key travel distance, pressure, operation mode, size, location, and tactile feedback shall be verified by ____________.

VERIFICATION RATIONALE (4.3.3.2)

Keyboard characteristics must be verified to assure usability.

VERIFICATION GUIDANCE (4.3.3.2)

These characteristics are normally verified by measurement and inspection.

VERIFICATION LESSONS LEARNED (4.3.3.2)

5.0 DEFINITIONS.
Within this handbook, the following definitions apply.

5.1 Average luminance.
The average of two or more luminance measurements taken at appropriate locations over a specified area.

5.2 Built-in tests (BIT).
Automated internal tests, which may be further defined as continuous or interrupting.

5.3 Conformal.
An image where the angles between points or objects match the real world. On a HUD, symbols which overlay objects or depict angles as the pilot sees them in the real world are called conformal.

5.4 Contrast definitions.
There are numerous expressions for contrast, contrast ratio, modulation, and various other similar quantities, with very little standardization of meaning or usage. The following definitions form a consistent set; most of the other definitions which are found are actually equivalent to one of these (but may be expressed differently) or are so rarely used that they should be avoided. These definitions are based on the following measurable quantities:

L_t, the total luminance of the image, or brighter area, including any background or reflected light, as measured in the specified lighting conditions.

L_b, the luminance of the background, or dimmer area, including any reflected light and any stray display emissions, measured in the specified lighting conditions.

ΔL, (delta luminance) the difference between the higher luminance (L_t) and the lower luminance (L_b). For a CRT, this is only light emitted by the display, that is, measured directly in a dark room. For devices which rely on reflectance changes (such as LCDs or painted-on instrument faces), ΔL cannot be measured directly; but it can be calculated as L_t-L_b.

L_{ul}, the luminance of an unlighted element; this will be the same as L_b for a CRT, but will be different for a device with discrete image elements, like an illuminated switch cap or a segmented LCD.

a. Contrast ratio (CR) or luminance ratio. $CR=L_t/L_b$, numerically equal to $(\Delta L+L_b)/L_b$, also = $1.0 + \Delta L/L_b$. This quantity ranges from 1.0 (no contrast) to approaching infinity, and is commonly used in CRT and HUD specifications. It is used not only because it is larger (more impressive) by one than the contrast definition (below), but because it makes sense and is easy to use where two luminances are being compared, such as between shades of gray on a CRT.

b. Contrast (C) or luminance contrast. $C=\Delta L/L_b$, numerically equal to $(L_t-L_b)/L_b$, also = CR - 1.0. This quantity ranges from 0.0 (no contrast) to approaching infinity, and is commonly used in instrument and control panel specifications. It is used in lieu of the contrast ratio definition only because it starts at zero, which is more logical to some people. Sub-definitions include C_l, which is the contrast of a lighted element against an unlighted element, and C_{ul}, which is the contrast of an unlighted element against its background.

c. Contrast as modulation (C_m). $C_m=(L_t-L_b)/(L_t+L_b)$, numerically equal to $\Delta L/(L_t+L_b)$. This quantity ranges from 0.0 (no contrast) to 1.0, and is often found in human factors research, such as in discussions of contrast sensitivity of the eye. It has been called contrast, Michaelson contrast, modulation, luminance modulation, or, when multiplied by 100, percent contrast, depending on the author. This quantity is consistent with "modulation" as defined in communications theory.

d. Luminance contrast. $LC=(L_t-L_b)/L_t$, numerically equal to $\Delta L/L_t$. This quantity ranges from 0.0 (no contrast) to 1.0, and was called luminance contrast in some older documents. It is equal to the C_m definition (c. above) for C_m =1.0 or 0.0, but is larger than C_m elsewhere. It is luminance difference divided by (normalized to) maximum luminance, rather than mean luminance or minimum luminance, and is rarely used.

5.5 Diffuse reflection.

Scattered or broken up reflection of light. The $BaSO_4$ reflectance standard used in photometric tests, and ordinary white paper, are examples of diffuse reflectors.

5.6 Display element.

The smallest addressable entity of the display. In the case of a color matrix LCD, the smallest addressable shutter or dot of an individual color. In the case of a segmented display, any of the shapes, characters or symbols made up of only one individual addressable entity. Sometimes called a "dot", a "segment", or (when a pixel is subdivided to spatially achieve color or gray shades) a "subpixel".

5.7 Fill factor.

On a matrix display, the transmissive or emissive area divided by the total image area, normally expressed as a percentage. Actually, the light transmission (in percent) of a display is a more significant performance parameter. Transmission is affected by the other things besides fill factor, such as the quality of the color filters.

5.8 Gray shade.

One increment in luminance, generally assumed to be a ratio of 1.41 (square root of two) brighter than the adjacent shade. This ratio is based on the traditional definition (in optics and photography) of a gray shade, and the number of gray shades displayable is often used as a benchmark measure of a display's dynamic range.

5.9 Gray level.
One increment in luminance. The size of the increment depends on the system. The number of levels is a measure of how finely a digitized image is quantified in luminance. For example, if a system uses 8 bits of data to define the luminance of a display element, the luminance can be set to any one of 2^8 (i.e., 256) levels, and these levels would (hopefully) be close enough together that a viewer will not notice the discrete edges (contours) where image luminance changes from one level to the next.

5.10 Line pair.
One bright line and the adjacent darkened space between that bright line and the next bright line, comprising a portion of a group of alternating bright and dark parallel lines. Note there are two lines per line pair, and each line must be active, i.e., can be turned "on" or "off."

5.11 Line rate.
In raster scanned systems, the total number of horizontal line times which occur in one complete frame time. Note that this is different from the number of active lines (those that appear on the screen) and the horizontal resolution (also dependent on things like bandwidth and spot size). For example, commercial TV in the US is 525 line rate, 485 active raster lines and has a horizontal resolution of around 300 lines.

5.12 Lines (of resolution).
The maximum number of alternate light and dark lines that can be resolved within a unit dimension, generally "lines per cm" (or inch), "lines per picture height," or just "lines", which can be assumed to be lines per picture width or height. On a device with discrete picture elements (pixels), the number of pixels is stated as the resolution, although it is not strictly equivalent to lines of resolution on an analog display. The units of "lines per picture height" for horizontal resolution, defined in EIA-RS-170, were used in many TV systems, but are now rarely used because of the confusion caused by expressing horizontal resolution in terms of vertical screen height, and the fact that it gives a lower (less impressive) number on a 4:3 aspect ratio (standard rectangular) display.

5.13 Malfunctions.
Equipment failures which render the equipment or equipment modes unusable.

5.14 Minutes and milliradians.
Units of angular measurement. 60 minutes of arc = 1 degree. 2 pi radians = a circle (360 degrees), therefore 1 radian = 57.3 degrees, 1/1000 radian (one milliradian) = 3.44 minutes of arc. Milliradians are convenient units for small angles because the size of the object, divided by the distance to the object (in the same units), gives its angular subtense in radians.

5.15 Occlude.
To block off or cut off, as when one symbol overlaps another and the one "in back" is partially hidden from view. "Occult" has a similar meaning and is sometimes used interchangeably.

5.16 Out-of-tolerance condition.
Equipment faults which cause the equipment to perform below specified performance limits but do not render the equipment modes unusable.

5.17 Pixel.
Contraction for "Picture Element". In a matrix display, the smallest element or group of elements which provides spatial information and can produce all of the color and gray level capabilities of the display. Note that some use pixel to refer to a single "display element", as defined herein. It may be necessary to use the phrase "color group" or "full color pixel" to clarify. See "Flat Panel Displays and CRTs" , by Lawrence Tannas and SAE-ARP-4256.

5.18 Self-tests.
Automatic, non-interfering performance testing employing either continuous or iterative monitoring techniques.

5.19 Specular reflection.
Mirror-like reflection, with the characteristic that the angle of incidence equals the angle of reflection. An image of your face, seen reflected in a display, is a specular reflection.

5.20 Quantities of light.

5.20.1 Candela per square meter (cd/m^2).

The cd/m^2 (also called nit for normalized intensity), is the S.I. (Systeme International d'Unites, or international system of units) unit for luminance. Luminance is used to measure light radiating or reflecting from a surface, such as the face of a CRT. A cd/m^2 is approximately 0.292 foot Lambert (1 fL approx. 3.43 cd/m^2).

5.20.2 Lumens per square meter (lm/m^2).

The lm/m^2, or lux (light flux) is the S.I. unit for illuminance (commonly called illumination). Illuminance is used to measure light falling on a surface, such as a desk or display surface. One lux is approximately equal to 0.0929 foot candles (1 fc approx. = 10.76 lux).

5.20.3 Candelas (cd).

The cd is the S.I. unit of luminous intensity (commonly called just intensity). Intensity is used to measure light coming from a point source in a given direction, such as the light coming from a landing light or anti collision light on an aircraft. It is also used to measure devices which are too small or non uniform (like LEDs) to be accurately measured in luminance units. It is roughly equal to the obsolete units of candles and candlepower. One candela = 1 lumen per steradian.

5.20.4 Lumens (lm).

The lm is the S.I. unit of luminous flux. Luminous flux is used to measure the total light coming from a source, such as an ordinary light bulb.

6.0 NOTES
Section 6 contains information of a general or explanatory nature. It contains information designed to assist in determining the applicability of the handbook.

6.1 Intended use.
This handbook entitled Electronically/Optically Generated Airborne Displays, is intended for use as guidance for developing a weapon system's electronically/optically generated airborne displays subsystem level specification.

6.2 Subject term (key word) listing.
The following subject terms (key words) allow identification of the document during retrieval searches.

displays

airborne displays

cathode ray tube

cockpit displays

CRT

head-up display

helmet-mounted display

LCD

liquid crystal display

multi-purpose display

multi-function display

sunshine legibility

6.3 Changes from previous issue.
This handbook contains most of the same material (with technical revisions) which was previously included in the Appendix to Air Force Guide Spec 87213 (AFGS-87213), titled "Displays, Airborne, Electronically/Optically Generated". Due to the extent of changes, the changes are not marked.

Custodian:

Air Force - 11

Preparing Activity:

Air Force - 11

Project No. 15GP-F110

APPENDIX A

HISTORICAL INFORMATION ON ELECTROMECHANICAL INSTRUMENTS AND DISPLAYED PARAMETERS

Forward

This appendix was derived from AFGS-87216, Instrument Systems, Airborne, which dealt almost exclusively with electromechanical instruments and is now canceled. Although electromechanical instruments are becoming obsolete and are being replaced by electronic displays, AFGS-87216 contained a wealth of rationale and guidance on presenting instrument information in the cockpit. This information has been collected into this appendix for use as a reference. Note that many stated requirements in this appendix are no longer valid with the current generation of aircraft and avionics - they are provided only as a historical reference. One should replace "is required" with "was required" when reading this material, since many of the requirements are not appropriate with electronic displays.

Contents

The following list of instruments/equipment are covered in this appendix.

In some cases both sensors and indicators are covered, since they were generally specified and developed together because of the tight integration needed with analog systems.

A.1 Acceleration display.
The acceleration display shows an instantaneous normal (z axis) acceleration of the air vehicle in units of gravity ("g"). It shall have the following characteristics: _________.

REQUIREMENT RATIONALE (A.1)

An acceleration indicator is usually provided on those aircraft which are limited in positive or negative g loading capability. It is also used in combat and to record maximum and minimum g levels the airframe has experienced.

REQUIREMENT GUIDANCE (A.1)

Most of these devices were mechanically operated from an acceleration sensitive spring/mass sensor located within the indicator itself. The sensor mechanism on these devices is geared directly to a pointer which will indicate the g-loading on a round dial display. Most of these devices also have a mechanism including two additional pointers which will allow the maximum positive and negative g reading to be retained after the aircraft has encountered those maximum load factors. A typical display would show the instantaneous pointer, maximum positive acceleration memory pointer, maximum negative acceleration memory pointer, and reset button. The reset button is provided for the purpose of allowing the memory pointers to be reset to the 1 g indication during or after each flight.

Some form of internal protection against acceleration forces incident to shipping is often necessary, particularly for mechanical accelerometers. A locking device can be incorporated in the mechanism which will prevent damage to the instrument if it is dropped or severely jolted in shipment.

Acceleration indicators for those air vehicles which require them may be provided in several forms. They may be round dial, self-contained mechanical instruments; vertical scale displays with remote sensors; or any form of electro-optical display with appropriate sensors. The following factors must be considered:

a. Range. The range of the accelerometer should be specified based on the mission and type of the aircraft. Typically, a high performance fighter aircraft has a range of g loading from approximately -2.0 to +8.00 g's, and therefore, a range of -4 to +10 g's on the accelerometer is reasonable. For a cargo/transport aircraft which has a mission with no high g loading, an accelerometer with a range of -2 to +4 g's could be used.

b. Accuracy. The limiting factor on most g meters is the design of the sensor. With a mechanical device, D+0.2 g's accuracy was considered to be the state-of-the-art. Electrically driven indicators with remote transducers can be designed to be more accurate; however, it is questionable whether or not an accuracy better than D+0.2 g's is required.

c. Response. The purpose of the g meter is to sense steady-state g loading on the aircraft. Acceleration loading due to vibration of the aircraft also exists. This g loading is a function of the frequency of vibration, and therefore, the g meter should be damped so as not to sense this portion of the aircraft g loading. Most accelerometers damp out any g loading due to vibration at frequencies above 5 Hz. This damping is critical in the design of the g meter, and any vibration above 5 Hz that is not damped out will be displayed by the pointer and make the display unacceptable.

d. Display. A typical display proven acceptable in USAF aircraft is shown in MIL-HDBK-27261 and STANAG-3330. As noted, the g meter should read 1 g when in a normal position with no g loading on the instrument since the mechanism should sense the earth's normal g force acting on the aircraft. Other displays such as head-up displays (HUDs), etc., may be considered if it can be shown that the display will be operationally acceptable. The maximum positive and negative memory feature should be incorporated in any considered display due to the fact that during aircraft maneuvering the pilot may exceed his allowable g loading limits without reading his accelerometer and will not know that he has exceeded the limit. The memory capability will provide the crew (pilot and ground crew) that information.

REQUIREMENT LESSONS LEARNED (A.1)

Design complexity and poor reliability have been experienced with some central test systems. High cost is another consideration. Self-test on certain individual instruments has been successful. Maintenance of the test systems has been a problem.

A.2 Attitude display.

The attitude indicator (AI) displays the air vehicle pitch and roll attitude with respect to the gravity vector and shall have the following characteristics: ________________.

REQUIREMENT RATIONALE (A.2)

Attitude indicators are used to determine, achieve, and maintain aircraft pitch and roll attitude in all phases of flight. The most critical use is during flight in IFR (Instrument Flying Rules) conditions. As such, it is a primary safety-of-flight display, and a minimum of two independent attitude references per aircraft are usually required.

REQUIREMENT GUIDANCE (A.2)

There are two basic types of attitude indicators: (1) self-contained AIs which contain a vertical sensor coupled to the display; and (2) the remote AI which is driven electrically by a separate attitude reference system. Electro-optical displays may be used, providing they meet the requirements of contrast ratio, etc., previously stated.

Self-contained AIs were frequently specified for use to provide standby attitude information when the primary attitude display fails. In the case of gyroscopic instruments, the gyroscope wheel has a certain coast-down time which provides a usable attitude display for several minutes in the event of a power failure. Self-contained attitude indicators have proven to offer size and weight advantages over remote standby attitude indicating systems. The following items must be given consideration when specifying attitude indicators:

a. Display. The common element of attitude indicators is that they all display aircraft pitch and roll attitude by means of a two-colored display (a spheroid or drum on some self-contained AIs). The upper half of the spheroid simulates the sky or above the horizon and is colored a light gray or light blue (blue is preferred in white-lighted applications). The lower half simulates the ground or below the horizon and is colored black or brown (brown is preferred in white-lighted applications). The intersection of the two colors represents the horizon line or zero pitch-and-roll reference. A fixed miniature aircraft symbol in the center of the display is the reference to which attitude is displayed. Upward movement of the horizon line indicates a dive maneuver and downward movement indicates a climb maneuver. Roll attitude is displayed by rotation of the horizon line, spheroid, and roll pointer which should be at the bottom of the display. Clockwise rotation indicates left wing down and counterclockwise rotation indicates right wing down. This attitude display convention simulates what the pilot would see if he were flying visually and observing the earth's horizon through the cockpit window. It is safety-of-flight critical that all attitude displays operate in this manner. Examples can be found in MIL-I-83336 and STANAG-3637.

b. Range. The range of the AI must be compatible with the air vehicle in which it is to be used. The range of electro-mechanical AIs is typically 85 degrees in climb and 85 degrees in dive with an unlimited range of 360 degrees in roll. The pitch range is usually limited by the vertical sensor. If loop maneuvers are to be flown, it may be desirable to specify maximum errors allowed during and after loops.

c. Pitch trim. Most attitude indicators used by the USAF incorporate a pitch trim adjustment to align the horizon line with the miniature aircraft symbol. This allows the pilot to "zero" the display when conditions require maintaining a relatively large angle of attack due to a heavy load or low airspeed for long periods. The zero index mark shows the pilot that some trim has been put in. Certain users, including some NATO nations, do not favor the incorporation of pitch trim for safety reasons. The range of pitch trim is typically 5 degrees to 10 degrees down to 10 degrees to 20 degrees up. These values are not critical and can be specified based on the normal angle-of-attack range of the aircraft.

d. Self-contained indicator. When a self-contained AI (vertical sensor and display combined) is to be specified, the following items must be considered:

(1) Static accuracy. The static accuracy of self-contained attitude indicators is usually specified at 0.5' in pitch and roll. An accuracy better than this is very difficult to measure and would simply be a matter of judgment on the part of the tester.

(2) Dynamic accuracy. Dynamic accuracy is that accuracy which can be expected to be maintained during various flight maneuvers. It is virtually impossible to test in the laboratory, and other means of specifying this requirement have been used in the past (see lessons learned).

(3) Caging. Self-contained AIs usually require a caging mechanism to bring the display to 0 degree in pitch and roll during start up or if the vertical sensor has deviated from vertical for some reason or another. It will be necessary to specify the panel tilt angle for self-contained AIs because it must be taken into account when designing the vertical sensor in the case.

(4) Power warning flag. The power warning flag tells the aircrew when power to the AI has been discontinued. It is desirable to have the flag remain from view as long as a usable attitude reference is maintained, such as in the coast-down mode of the gyroscope wheel, if used. If the flag does come in view immediately upon power failure, it must not obscure the display if the AI design provides attitude information for a limited time after power failure.

e. Remote driven indicator. The following factors must be considered when specifying AIs that are driven from a remote vertical sensor:

(1) Compatibility. The indicator must be designed to be compatible with the vertical sensor planned to be used. If the vertical sensor has an all-attitude capability, the indicator should also have this capability.

(2) Accuracy. An accuracy of $\pm$0.5 degree within $\pm$30 degrees of zero pitch and roll is necessary and is easily attained. Precise aircraft attitude control and manual dive bombing accuracy are dependent on the accuracy of the attitude indicator. Accuracy at higher attitudes becomes less critical, but it is typically $\pm$1 degree.

(3) Sensitivity. A sensitivity of $\pm$0.25 degree or better is necessary to provide detection of minute attitude changes. Sensitivities greater than $\pm$0.25 degree are not desirable, as undetected attitude changes, especially at high speeds, can cause difficulty in maintaining constant altitude.

(4) Follow-up operation. The pitch and roll follow-up rates should be compatible with the maximum pitch and roll rates of the aircraft without excessive lag. Typical rates for high performance aircraft would be 60 degrees/second in pitch and 300 degrees/second in roll. Typical AIs have 90 degrees/second pitch capability and 300 degrees second roll capability with lag no greater than 3 degrees and 10 degrees, respectively.

(5) Hunting and jumping. It is very important that the attitude display operate smoothly with no noticeable sticking, hunting or jumping, as these conditions are generally accepted as indications of a malfunctioning indicator. In addition, non-smooth operation would be distracting and annoying to the pilot.

(6) Pitch scaling. For 3-inch case size primary attitude indicators, the pitch display may be expanded to provide the necessary resolution to easily detect small attitude changes. The expansion ratio is typically 1.5 to 1. Expanded pitch displays may be provided in larger AIs if the flight characteristics of the aircraft dictate the need to be able to detect very small pitch attitude changes. Too much expansion could be undesirable as it could result in a noisy display (too much sphere motion). Expansions in the range of 1.5 to 1 to 2.0 to 1 have generally proved acceptable.

(7) Malfunction warning flag. The AI is a primary safety-of-flight instrument, and if it fails and gives erroneous information without the pilot's knowledge and he continues to assume it is right, the aircraft could be put into a hazardous and possible non recoverable attitude. For this reason it is mandatory that the AI contain maximum self-monitoring capability.

The following are conditions which should actuate the warning flag:

(a) Loss of power to the indicator or sensor.

(b) Invalid pitch or roll attitude signals.

(c) Internal failure of the AI display mechanism, such as amplifier failure, servo-motor failure, etc.

REQUIREMENT LESSONS LEARNED (A.2)

Dynamic or flight accuracy of gyroscopic-type self-contained attitude indicators is difficult to verify. It can only be accomplished under actual flight conditions and the AI compared to an accurate reference, such as an inertial navigation system.

It has been found from experience that dynamic errors can be held to within reasonable limits if certain characteristics of the gyroscope are maintained. These characteristics are:

a. Drift rate. The free gyroscope should not drift more than 0.75 degree per minute in either axis when tested on a 3-axis motion table (Scorsby).

b. Erection rate. The erection rate of the gyroscope is usually specified at 1.9 degrees to 3.1 degrees per minute in both pitch and roll. The typical value is approximately 2.5 degrees per minute. If the specified erection rate is too high, significant errors will result from accelerations and turns. If the erection rate is too low, the gyroscope will not remain erect.

c. Erection cutout angle. The erection cutout angle is usually specified at 6 degrees to 8.5 degrees in pitch and roll for 2-inch indicators. The typical value is approximately 7 degrees. The cutout angle for 3-inch indicators is usually specified at 7 degrees to 10 degrees in pitch and roll. Indicators with electrical erectors will have a smaller erection cutout angle in the roll axis and may have no erection cutout in the pitch axis.

The performance of remote attitude indicators is based on the accuracy of the remote vertical sensor. However, the AI must smoothly follow the output of the sensor. Experience has proven that hunting and jumping magnitudes less than 0.04 inch total amplitude provide the degree of smoothness that pilots will accept. The rates at which this tolerance is most critical and must be adhered to are the lower rates between 0 degree and 20 degrees/second.

A.3 Attitude director indicator (ADI).
The attitude director indicator shall provide attitude information combined with action director information superimposed on the attitude display. It shall have the following characteristics:

______________________.

REQUIREMENT RATIONALE (A.3)

Attitude director indicators perform the same function as the attitude indicator in addition to displaying additional flight control information, such as steering commands, rate of turn, slip, etc. These additional functions, incorporated into one display, reduce pilot cross-check workload, which is very important during high workload flight, such as during instrument approaches.

REQUIREMENT GUIDANCE (A.3)

The information and requirements for attitude indicators apply to the ADI. In addition to attitude information, the ADI provides pitch and bank steering command displays which are controlled by a flight director computer. The steering command display typically consists of two bars. A vertical bar provides roll steering commands and a horizontal bar provides pitch steering commands. The flight director computer which drives the bars is mechanized such that the bars will be centered on the miniature aircraft symbol when the aircraft is on a flight path that will either result in the aircraft flying to the desired flight path or will maintain the aircraft on the desired flight path. The command bars are typically used during ILS approaches and in intercepting and flying a desired heading or TACAN radial. The command bars are biased out of view when not in use. A warning flag is provided to warn the pilot of an invalid or failed flight director computer. The ADI display also incorporates a glideslope deviation scale and pointer, a rate-of-turn needle, and a slip indicator. The glideslope pointer indicates aircraft position relative to the ILS glideslope centerline and receives its input signal directly from the ILS glideslope receiver. The rate-of-turn indicator indicates turn rate of the aircraft where full scale (two needle widths) is normally equivalent to a standard 2-minute turn. The rate-of-turn needle receives its input from a rate-transmitting gyro or a derived rate-of-turn output (heading rate) from an attitude heading reference system.

Like the attitude indicators, the ADI should have a malfunction warning flag for the attitude portion of the indicator.

A pitch trim control knob may be provided. If used, it shall be in the lower right side of the indicator (see paragraph A.2 for details). The ADI can incorporate other displays depending on the type and mission requirements of the aircraft. Typical ADI functions include the following:

a. Rising runway symbol. This symbol displays the main landing gear radar altitude above the runway. It comes into view normally at 200 feet radar altitude and moves up towards the miniature aircraft symbol as the aircraft descends. The symbol will coincide with the bottom of the miniature aircraft when the main landing gear wheels touch the ground. The rising runway display should be included in ADIs intended for use on aircraft that will be required to make Category II (1200-foot runway visual range and 100-foot decision height) landings. The symbol receives its input from a radar altimeter.

b. Expanded localizer display. Localizer deviation is displayed with a full-scale range of one dot. The localizer signal is received directly for the ILS localizer receiver. Ideally, this display should be combined with the rising runway symbol although a separate scale and pointer in the lower part of the ADI can be used. Incorporation of a localizer display in the ADI will minimize cross-check workload during the final phases of an instrument approach. This function should be incorporated in ADIs intended for aircraft that will land in weather minimums lower than Category II. An associated failure warning flag is required.

c. Speed command display. This display consists of a pointer that moves in a vertical path normally located on the left side of the ADI display. The operation of the pointer is such that if it is above center, the aircraft approach speed is fast and if it is below center, the aircraft approach speed is slow. With the pointer centered, the aircraft is on the proper approach speed. The input for this display is an angle-of-attack based signal. This display should be included in ADIs intended for aircraft that will land in weather minimum lower than Category II. An associated warning flag to warn of invalid inputs is required.

d. Heading. Some ADIs incorporate a 3-axis sphere. The third axis is used to display aircraft heading using appropriate markings. An example of this ADI can be found in MIL-I-27619.

e. Attitude display configuration. Generally, the attitude display will conform to that described in A.2.

f. Pitch and bank command characteristics. Deflection of the command symbol or symbols should be linear in degree with respect to the input signal. Damping and response should be such as to minimize lag and overshooting. The display must be stable as practical under rough air and vibratory conditions. Accuracy and scale factors shall be sufficient to allow the pilot to maintain the desired flight path without excessive overshooting or snaking. The effect of acceleration on the display accuracy must be negligible.

g. Glideslope deviation scale factor. The scale factor should be such that one-dot deflection is equivalent to a 0.25 degree deviation from glideslope centerline and shall require an input of ___________________. Two-dot deflection shall be equivalent to 0.5 degree deviation and shall require an input of ____________. Pointer deflection must be linear with respect to the input signal. The pointer mechanism must be overdamped. The effect of acceleration on pointer accuracy must be negligible. **NOTE**: The input signal depends upon the characteristics of the flight director computer (see A.7).

h. Turn and slip sensitivity. The rate-of-turn and slip indicator should meet the requirements necessary to control the air vehicle. Guidance can be found in A.27.

i. Auxiliary attitude outputs. Outputs of the pitch-and-roll display position can be provided if necessary for use by an external attitude comparator monitor.

REQUIREMENT LESSONS LEARNED (A.3)

The characteristics of the ADI depend upon the flight characteristics of the air vehicle. Typical values of accuracy, response, and damping, which have proven acceptable for the pitch-and-roll steering commands, are a linear response within 7.5 percent of the proportionate full-scale value of the input, damping such that overshoot is held to less than 1.5 percent and response time of 1/3 second.

It has been found that the use of "raw" deviation data applied to the steering commands is unacceptable.

If the air vehicle has redundant pilot and copilot attitude displays and reference systems, it is recommended that an attitude comparator monitor be installed. The comparator monitor compares the two attitude display systems, and if they differ, a failure warning is annunciated. The ADIs must be mechanized to provide signals at the indicator connector suitable for use with a comparator monitor. The signal characteristics are typically a synchro resolver stator and rotor. Two sets are required--one provides roll-axis position and the other provides pitch-axis position.

A.4 Clock/timer.
The clock or timer shall include a display of real time. The following characteristics will be provided: ______________________.

REQUIREMENT RATIONALE (A.4)

The provision of a clock is basic to any air vehicle. In addition to providing real time, most clocks provide elapsed-time measuring features which are required for many functions.

REQUIREMENT GUIDANCE (A.4)

The clock may be either mechanical or a numeric solid-state electronic type which displays time of day in hours, and minutes and has an elapsed-time capability in seconds. When the mission requires a bomb timer, it should be a solid-state electronic design.

a. Clocks. The following characteristics should be considered when specifying clocks and timers:

(1) Display. The display may be an analog, numeric, or a combination of analog and numeric displays. In addition to a display of time of day, elapsed-time and countdown displays may be specified. Historically, clock displays have consisted of hour, minute and second hands, 12 hours being used for one revolution of the hour hand. Straight numeric readout clocks have been tested by the Air Force, and most of the pilots accepted the display. If a numeric display is desired, it should be carefully evaluated for acceptance by the users, including possible foreign buyers/users, before it is specified. Numeric readouts should display real time from 00:01 to 24:00. Elapsed time and countdown time may be analog or numeric. The time period capability must satisfy mission requirements.

(2) Accuracy. The accuracy must be sufficient to meet mission requirements. It may be necessary to specify accuracies at high and low temperature as well as ambient temperature, depending upon the clock design and its characteristics.

(3) Elapsed-time actuator. If equipped with an elapsed-time display, a push button must be provided to start, stop, and reset or obliterate the display. When the button is pushed, the display should start to count up. When the button is pushed again, the display should freeze. When the button is pushed a third time, the display should reset or disappear from view.

(4) Countdown mode actuation. If a countdown mode is required, a push button should be provided to initiate the countdown mode of the clock. A second actuation of the countdown push button should zero the countdown mode.

(5) Time set. A suitable means must be provided for resetting the time of day display when it does not correspond to actual time.

(6) Power. Mechanical clocks have been spring-wound types since their inception. New technology permits the use of a self-contained battery or external power, but the use of self-contained batteries in instruments has not received wide approval in the Air Force due to logistics problems.

(7) Power interrupts. If an electrical input clock is specified, the clock should be capable of operation during power interrupts of the longest duration anticipated.

(8) Running time. Running time will depend upon the clock design. Spring-wound clocks will normally run for eight days.

(9) Self-test. If numeric light-emitting display is used, a push-to-test switch should be provided which shall cause all digits to appear.

(10) Case size. A 2-inch nominal case size is normally specified for clocks. Special purpose clocks may have to be larger.

b. Bomb timers. When specifying bomb timers which are sometimes used on a backup system to a primary weapons delivery system, the following modes of operation require consideration:

(1) Clock mode. Controls and mode select capability may be used to provide a time-of-day readout.

(2) First and second stopwatch modes. Controls and mode selection capability may be specified to provide stopwatch modes capable of counting up to the time required for the bomb delivery.

(3) Single countdown timer mode. Controls and a mode select capability may be provided to allow a preset time to be selected. The bomb/timer, upon being started, will count down to zero. An output signal and a visual indication of zero time should be provided.

(4) Dual countdown time mode. In this mode, the timer functions as a bombing pullup and release timer. Controls and mode selection capability must be made available to allow two preset timers to be selected. Upon initiation the bomb/timer counts down to zero on the first present time. At zero an output signal is provided. When the first preset time reaches zero, the timer automatically switches and starts to count down the second preset time to zero. Again, when zero is reached, a separate output signal is provided. Visual cues are provided when each time reaches zero.

REQUIREMENT LESSONS LEARNED (A.4)

A.5 Engine pressure ratio system (EPR).
The EPR display shall receive signals from an EPR sensor and shall display EPR values to the aircrew. The EPR sensor shall sense the engine inlet total pressure, the turbine exhaust total pressure, divide the exhaust pressure by the inlet pressure, and provide a signal proportional to this nondimensional ratio for use in a display or in control of an aircraft. The performance of the system shall be as follows:

______________________.

REQUIREMENT RATIONALE (A.5)

Depending upon the type of engine used in the weapons system it may be necessary to provide an indication of EPR to indicate the amount of thrust being operated by the engine.

REQUIREMENT GUIDANCE (A.5)

Engine pressure ratio (EPR) is the ratio of the total pressure in front of the engine compressor divided into the total pressure behind the turbine. EPR is a dimensionless number normally in the range of 1.0 to 3.5. Turbofan engines tend to have lower EPRs because of the power extracted by the turbine to drive the fan. Some commercial EPR systems have the ability to compute and display an EPR of less than 1.0. This condition may be encountered on a large fan engine that is throttled back to flight idle for descent. An EPR of 1.0 or less means that even though the engine is running, the net effect on the aircraft is a negative thrust. It is recommended that the military not require the capability to compute display EPR less than 1.0 as it increases the complexity of the system more than it increases the usefulness of the system.

Related to EPR is FPR (fan pressure ratio). On large fan engines some commercial users require a display of the fan pressure ratio. While FPR gives a good indication of the thrust being produced by the fan, it is difficult to compute because of the small differences (low ratio) between the two pressures being divided. Additionally, the plumbing requirements impose a much greater weight penalty than does an EPR system. The use of FPR by the military is not recommended.

EPR is applicable to any fixed nozzle engine. EPR is not suitable for use on any variable nozzle engine, even if the engine employs a two position nozzle. This is because of variations in nozzle geometry and control. It would be possible for two engines to have the same EPR but be producing quite different levels off thrust. For variable nozzle engines, use of a thrust computing system is recommended (see paragraph A.26 for a thrust computing system).

The following requirements should be specified in procurement documents:

a. Range. Generally speaking, the EPR transmitter is designed specifically for the engine it is to be used with. An off-the-shelf transmitter may be used only if it very closely matches the requirements of the engine. This is because an unused range is extremely costly in terms of accuracy. Normally, a 0.08 percent unused range is adequate to provide for engine growth.

b. Accuracy. Traditionally, accuracy requirements are driven by the capability of the EPR transmitter manufacturer. EPR accuracies are always expressed in terms of thousands of an EPR unit. Different tolerances are required for different pressures. The larger tolerances are allowed at the lower pressures. The 1.000 point is significant because it provides an operational point that can be checked prior to engine starting. A typical accuracy requirement would be D+0.020 EPR units.

c. Response. The system should be able to respond just slightly faster than the engine can change its pressure output. Many times when a new EPR system is flight tested, there is a noticeable "jitter" in the pointer and counter. This problem can usually be solved by installing pressure dampers in the high pressure line where it enters the transmitter.

d. Sensitivity. At higher pressures more liberal tolerances for sensitivity are allowed. Sensitivity requirements are normally in the range of 0.0008 to 0.15 inches of mercury. Essentially, sensitivity is a measurement of the internal "stickiness" and "looseness" within the transmitter and indicator.

e. Attitude operation. Even if the aircraft is not intended to operate at all attitudes, the transmitter should be capable of operating at all attitudes. This is really a test (which becomes a requirement to the manufacturer) to assure that internal moving parts are kept in good mechanical balance. A well-balanced system will be more immune to wear due to vibration.

f. EPR limit or command. Many EPR indicators incorporate manual or automatic command "bugs" or limit markers. These markers are useful during takeoff and other flight modes. EPR command "bugs" are used with some fuel savings advisory systems to direct the pilot to the most efficient EPR range.

REQUIREMENT LESSONS LEARNED (A.5)

It is advisable to make the pressure lines and the transmitter connections two different sizes. A one-fourth-inch line and a five-sixteenth-inch line are sometimes used. There may well be twelve or more connections in the lines between the engine and EPR transmitter. If the lines are made the same size, sooner or later someone will cross-connect the lines and destroy a transmitter.

A.6 Engine temperature display.
The engine temperature display shall receive signals from an engine temperature sensor and shall display temperature in degrees Celsius to the aircrew. The display shall have the following characteristics: ______________________.

REQUIREMENT RATIONALE (A.6)

The temperature indication is used to avoid high temperature damage to the engine, determine proper engine operation, and detect or avoid hot starts during engine startup.

REQUIREMENT GUIDANCE (A.6)

An engine temperature display is provided for each engine and gives an indication of the engine operating temperature. The display receives a temperature signal from the engine. This is normally, but not necessarily, a thermocouple signal generated by a harness of thermocouples located in the engine gas stream. The thermocouples should be Type K (chromelalumel). When other types of engine temperature sensors are used (such as the optical pyrometer), the indicator must be tailored to the specific output of the sensor.

The following requirements need to be addressed when specifying engine temperature display:

a. Range. The range of the display shall be expressed in degrees Celsius. The range specified should be such that the lowest operating engine temperature at any operating condition (e.g., altitude, airspeed, throttle position, etc.) and the highest possible temperatures are included. The range should be limited to these levels to maintain the smallest usable span between the lowest and highest temperatures. The highest temperature should also be limited by the useful range of the sensor employed in the indicator system.

b. Accuracy. The accuracy requirements specified should be no greater than needed--normally ±5 degrees C in the most accurate region of the display. The display may be broken into regions of differing accuracies which are dependent upon the need for such accuracies. Accuracies should be specified for both normal room temperature operation, operation at the extremes of ambient operating temperature, and operation during reliability testing.

c. Warm-up response. The response requirement specified should be in the form of response to a step change of the input temperature signal. The size of the step change may be specified by defining the starting and ending indication input temperatures of the step change. The tolerance (settling-out characteristics) of the final indication and the time within which this final indication is reached should be specified. These requirements are dictated by the need to detect abnormally high temperature rise within the engine during a hot start condition. A suggested adequate response is 6 seconds to a 1000 degree C step change within $\pm$20 degrees C.

d. Display. The display may be either round dial or vertical scale. Round-dial displays are normally of the 2-inch diameter type. Greater accuracies are obtained by use of supplemental counters or expansion of the scale in ranges of greater needed accuracies. The normal operating position during cruise should be approximately at the 9 o'clock position of the round dial.

e. Thermocouples. The display must be compatible with and calibrated for use with the specific type of thermocouples to be used on the engine. Standards (NBS) 125. Monograph Thermocouple characteristics are given in the National Bureau of Standards (NBS) Monograph 125.

f. Grounding of thermocouple extension wires. A maximum shift of indication when either thermocouple lead is connected to the ground or low potential side of the input power supply should be specified. The grounding may be at any point between the thermocouple and the interior of the display. Typical limits are $\pm$2.0 degrees C.

g. External thermocouple circuit resistance. The display shall be designed such that a change in thermocouple circuit resistance between the hot junction and the indicator produces a negligible or small change in indication. A suggested adequate tolerance is 5 degrees C.

h. Thermocouple cold junction compensation. The display should be designed such that the thermocouple circuit cold junction is located within the display. Electronic compensation for the cold junction ambient temperature must be provided. Temperature control or standard cells must not be used in the cold junction circuitry. The compensation must be such that the indication accuracy is as specified regardless of the temperature of the cold junction.

i. Optional features. The display may include a settable maximum temperature recording pointer or a set of contacts which close at a certain temperature to energize a remote over temperature warning light.

REQUIREMENT LESSONS LEARNED (A.6)

A.7 Flight director system (FDS).
The FDS shall display the air vehicle interception and tracking of course, heading, attitude, and glideslope, based on present position, heading, desired position, and rate of convergence. The FDS will continuously calculate the proper pitch, bank, and power to perform the desired maneuver. It shall conform to the following: ______________________.

REQUIREMENT RATIONALE (A.7)

When crew workload associated with operation of an aircraft is very high, flight director systems may be employed to provide relief. Factors bearing upon the decision to employ the flight director shall include aircraft speed (and associated aircraft control ability), complexity of aircraft systems and/or subsystems, and the operating environment. In certain applications flight director systems may not provide sufficient relief, and the use of automatic flight control systems must be considered (e.g.,: all-weather landing and high-speed terrain-following).

REQUIREMENT GUIDANCE (A.7)

a. General. If a flight director is to be employed, components of the system must be specifically identified, including:

(1) Attitude Director Indicator (ADI) and/or Head-up Display (HUD).

(2) Horizontal Situation Indicator (HSI).

(3) Flight Director Computer (FDC).

The FDC may be analog, digital, or hybrid and may be dedicated equipment or part of a central computer/processor. Regardless, the control algorithms must be carefully specified to assure satisfactory system performance.

(4) Flight Director System Control Panel.

The control panel must provide a means for crew selection of navigation modes, manual heading mode, and OFF (or standby) mode. Positive indication of the operating mode must be provided. When automatic switching between manual heading submode and other navigation modes is employed, indication of the operating submode must be provided at the control panel or on the primary flight instruments.

b. System interface. Specific equipment which comprise the flight director system must be identified to establish system interface requirements. In addition, applicable equipments in the following list (if they provide input to the FDC) must also be identified (see 3.8):

(1) Attitude and Heading Reference (AHRS, DG/VG, or INS).

(2) Navigational Radio Receivers.

(a) Tactical Air Navigation (TACAN)

(b) VHF Omnidirectional Range (VOR)

(c) Instrument Landing System (ILS)

(d) Microwave Landing System (MLS)

(3) Radar Altimeter

(4) Air Data Computer

(5) Data Link Receiver

c. Flight director system (computer) logic. The flight director system may be utilized to reduce pilot workload in intercepting and tracking course, heading, altitude, or glideslope. Based upon present position, desired position, and the rate of convergence, the flight director computer continuously calculates the proper pitch, bank, or power to perform the desired maneuver (the commands are presented on the control displays/indicators). One of the following methods of displaying commands can be used:

(1) Pitch and bank cross pointers (in the ADI). When the aircraft is not properly positioned for course intercept, the vertical steering pointer is offset. By banking the "miniature aircraft" toward the pointer, the pointer moves toward the center of the ADI. By maintaining the pointer at center, the computed steering commands are satisfied. The computer will recognize proximity to and rate of convergence on the desired course and will supply appropriate commands to permit asymptotic intercept and stable tracking of the desired course. The above method of operation is equally applicable to vertical steering. When steering commands displayed on the horizontal pointer are satisfied, the aircraft will intercept and track the desired vertical path.

Power commands may also be displayed on ADIs containing a Fast-Slow display. The above system description is identified as the "conventional FDS" or the "2-cue system." A variation of this system is the integrated cue system in which a single cue is utilized; it is analogous to a pivoted horizontal pointer--when the cue pivots, the pilot must introduce bank to satisfy roll commands and as the cue transitions vertically the pilot must introduce pitch to satisfy steering commands.

(2) Three-cue flight director system (3-Cue FDS). This type of system is used primarily for V/STOL aircraft. AS in the conventional system, the vertical pointer furnishes guidance for lateral steering. However, the horizontal pointer is utilized to maintain reference airspeed by controlling pitch. The third cue (normally a scale and pointer similar to the glideslope display in the ADI) is utilized for vertical path control (ILS glideslope tracking, altitude hold, or climb/descent rate).

(3) Electro-optical displays (HUD, VSD, EADI). These types of displays utilize electronically-generated symbols to display flight director steering commands. The control logic associated with these displays is identical to conventional displays. In some aircraft the outputs from the FDC are scaled such that flight director steering commands are displayed on both HUD and ADI simultaneously.

d. Modes of operation. There are several modes of operation for flight director systems. Accordingly, specific modes of operation for a particular flight director system/weapons system must be specified. In addition, many modes are comprised of two or more submodes and depend upon automatic beam sensing and switching to effect submode changing. These submodes and operating regimes must also be specified, as well as automatic switch functions. The following modes (which may also be submodes) are provided:

(1) Manual heading mode. The pilot must select the desired reference heading (setting HDG on the HSI or similar control/display/flight control panel). The flight director system uses preset heading and reference heading to generate the proper steering commands to turn to and maintain the reference heading. The standard rate of turn is 3 degrees per second.

(2) Data link mode. This mode is most often an adaptation of the manual heading mode except that the heading set function is remotely controlled by a ground station/mission controller.

(3) Inertial navigation system (INS) mode. Desired course is established by a central navigation/mission computer by way-point identification. Deviation from course, as measured by an INS, provides a course error reference upon which to base lateral steering commands.

(4) Radio navigation mode(s). The desired radio reference (VOR/TACAN/ILS/MLS/etc.) must be selected, and reference course identified by setting the CRS on the HSI or similar control/display/flight control panel. The FDS senses present position (heading and course error), desired course, and rate of convergence to generate the proper steering commands to capture and track desired course. Some flight director systems employ submodes and automatic submode selection in this major mode of operation. When course error is great, the manual heading submode is used and the pilot must set reference heading to initiate course capture. When approach to course is sensed, the FDS will automatically switch to the course capture (radio navigation) submode. When submodes are not employed, the course intercept angle must be limited (normally to 45 degrees) and the FDS will command a turn to the 45 degree course intercept angle (when course error is great) immediately upon selection of the radio navigation mode.

(5) Approach mode. In this mode, the FDS (or operator) first assures that ILS/MLS course capture has been effected (per paragraph "b" above). After course is attained, the operator or system will select the vertical path (glideslope) submode. Automatic systems will sense approach to glideslope and will select the approach mode at the proper time. In some systems, radar altitude is also utilized to control glideslope steering sensitivity to desensitize steering commands as the glideslope beam narrows near the decision height. If altitude-hold mode is active prior to the approach, glideslope steering shall override altitude-hold upon sensing approach to glideslope.

(6) Altitude-hold mode. In most applications, the pilot must manually fly to the desired (reference) altitude. Upon reaching this altitude, he will select the altitude-hold mode. In more sophisticated systems, the pilot may select the reference altitude (barometric or radar altitude) before reaching it. The FDS will command proper pitch and obtain and maintain the reference altitude.

(7) Climb-descent modes. This mode is generally used in conjunction with the airspeed-hold mode. The pilot must set reference vertical speed in addition to airspeed. The control parameter is power (i.e., a 3-cue FDS). As in the airspeed mode, the climb or descent speed may be manually selected or the existing rate at the time of mode selection may be the reference speed (the method of selection must be specified).

(8) Airspeed-hold mode. In this mode, a "fast-slow" cue is used in conjunction with manual control of power. Reference speed must be set and employed in conjunction with engine dynamics and control characteristics to determine proper throttle commands. By maintaining the power cue at the command reference point, the pilot will attain and maintain the reference airspeed. Such command may be displayed on the FAST-SLOW display on some ADIs or similar display on electro-optical displays. In simpler systems, the airspeed-hold mode will simply maintain that speed which was present at time of mode selection.

(9) Terrain-following mode. This mode is used in conjunction with forward-looking radar. It is normally mechanized as a rate climb/descent mode such that when terrain falls within a predetermined envelope (template) ahead of the aircraft, a climb command is issued; when no terrain is within the specified envelope, a descent command is issued. Capability to track the desired flight path is dependent upon flight performance of the basic air vehicle, but once the appropriate template is defined, the FDS must provide very high probability of meeting required tracking accuracy.

e. FDS performance criteria. Specific performance criteria with respect to course intercept (maximum allowable overshoot, number of overshoots, and time to stabilize) must be tailored to each aircraft. FAA Advisory Circular 120-29 may be used as a guide. In establishing this criteria, pertinent aircraft performance requirements and characteristics must be established (i.e., cruise speed, approach speed, course intercept angle, and distance to station, including expected range of all parameters listed). Course tracking criteria shall also be specified. For most applications deviations from course centerline after course capture is less than 1/2-dot (course deviation scale on HSI); further, there must be no sustained oscillations about course centerline. Crosswind compensation is normally provided such that when operating in crosswinds up to 10 percent of aircraft speed (or 20 degree crab angle), there is no steady-state beam standoff. Navigational radio aids to be employed must be specified; particular attention is directed to tailorable ILS in which localizer width may be as narrow as 3 degrees (standard width is 5 degrees).

NOTE: 1/2-dot deviation has the following real values for a standard ILS:

TACAN - 2-1/2 degrees

VOR - 2-1/2 degrees

ILS-LOC - 5/8 degrees

f. Control algorithms (and associated control parameters). To assure understanding of the control algorithms and mode control logic, simplified diagrams of lateral steering circuits, vertical steering circuits, beam sensor circuits, etc., shall be provided. In addition, tables of values of gains and time constants associated with these diagrams shall be provided. The latter shall be presented as nominal values and allowable tolerances.

g. System safety. The following requirements are provided to assure safe use of the flight director system:

(1) Raw data (course deviation display, glideslope deviation display, etc.) upon which the computed steering commands are based shall be displayed concurrently with flight director data to permit operator assessment of system performance, (e.g., ILS localizer and glideslope deviation shall be displayed whenever ILS approach mode steering commands are displayed.)

(2) Failure warning. The following features shall be considered standard:

(a) Flight director command cues shall be stowed out of view whenever the reference signal source (navigational radio, air data computer, etc.) for the selected mode of operation has failed or whenever the flight director computer has failed. (An acceptable alternative, if an existing ADI design is to be utilized, is the employment of failure warning flags--one for each steering pointer.)

(b) Failure warning flags or symbols shall be provided to assure validity of navigational radio information, air data computer, etc., on which the FDS depends.

(c) When variable gain features are employed, the system shall be designed to revert to a single nominal value in the event of gain controller failure. In most flight director systems which use variable glideslope gain (in approach mode), the gain is desensitized to the lowest possible gain upon sensing that radar altitude input is invalid.

Basic requirements for a FDS are found in MIL-F-26685.

REQUIREMENT LESSONS LEARNED (A.7)

Possible disorientation can occur if the HUD and ADI do not agree. For example, the F-16 uses normal flight director data on the HUD but only raw data on the cross pointers in the ADI. This is not a recommended practice because the HUD pointer display may be centered, while the ADIs are not.

A.8 Rate of fuel flow system.
The rate of fuel flow system consists of a display used in conjunction with a flow sensor. One display is used for each engine to display rate of fuel flow in ________________________ (units). The system requirements shall be as follows: ________________________.

REQUIREMENT RATIONALE (A.8)

Fuel flow is used for engine starting, calculating flight time remaining, and giving an indication of thrust output. It is also used for engine fuel control trimming and on tankers to display rate of fuel flow transfer.

REQUIREMENT GUIDANCE (A.8)

Fuel flow measurement systems used on Air Force aircraft are to be of the mass measuring type. Most of the transmitters in current use are of the angular momentum type. Mass flow measurement is required because the heat content of a fuel is measured in heat units per mass and engine output is directly proportional to the heat content of fuel assuming a given engine efficiency. Fuel flow is measured in pounds per hour (PPH) or kilograms per hour (KPH).

The following items must be considered and specified for fuel flow systems:

a. Range. The lower range should be adequately low to provide an indication of flow for engine start. The lower limit will vary depending upon the overall range of the system. It is difficult to obtain a dynamic range of much greater than 200 to 1 in most mass flow systems; therefore, if a 100,000-pound-per-hour (PPH) maximum range is required the low limit will be around 500 PPH. The upper limit may be the total core engine plus after burner flow or may be limited to core flow only depending upon mission requirements and necessity for afterburner monitoring, fuel-used computations, etc. The highest flow currently used is on the F-15 having a 100,000 PPH capability. The range may be specified in kilograms per hour on aircraft destined for use in countries using the metric system. The range of systems used for refueling can go as high as 600,000 PPH or higher.

b. Accuracy. The accuracy of fuel flow systems is variable depending upon the flow rate. Typically, mass flow transmitters have a "bathtub-shaped" curve with less accuracy at the low and high-flow rates and greater accuracy in the mid-flow range. Indicator accuracies are usually constant over the entire range. Mid-range accuracies of transmitters are usually about +1.0 percent of reading. It will be necessary to prepare a table of accuracies versus flow rates in the detail specification. Accuracies should not be greater than required at each flow rate specified. Tolerances at high and low temperatures will be greater than at room temperature and will have to be specified accordingly depending upon the temperature extremes expected and the accuracies required.

c. Response. Specification of fuel flow system response may be required for two reasons; to follow rapid throttle movements and to calibrate fuel control systems. Typical throttle response times would require the system to respond to a full-scale step input within 1 percent after 3 to 5 seconds. If the system is to be used for fuel control calibration, the response time can be as low as 2 seconds, and the flow rates must be tailored to cover the rates required for calibration. The response time may be specified for the transmitter only assuming the fuel flow readout will be an X-Y plotter or other display.

d. Display. Fuel flow displays are typically 2-inch round dial indicators installed in 2-inch clamp-mounted cases per MS-33639. The scale should be oriented so that the cruise range fuel flow rate is positioned at 9 o'clock. Displays may be varied depending upon mission requirements and the aircraft panel design. Digital numeric readouts, vertical scale indicators or CRTs may be used.

e. Transmitter. The fuel flow sensor/transmitter must be of the true mass flow measuring type. The output signal shall be proportional to the rate of flow and may be analog or digital in format. If a digital signal is specified, it shall be compatible with MIL-STD-1553 or with ARINC standards, depending upon end usage.

f. Pressure drop. Pressure drop is important because it requires pumping force to overcome. In some aircraft pressure drop is critical when the pumps fail and the engine must be fed by gravity flow. A typical pressure drop in a 100,000 PPH transmitter is 2.5 psi at flow. Pressure drop generally increases by a square power of the flow. The pressure drop requirement is based on several factors, such as the requirement for gravity feed, auxiliary pumping equipment, fail-safe considerations, etc.

g. Pressure. The static pressure that the transmitter must withstand without rupture or leakage must be specified. The component should be capable of withstanding a proof pressure of two times maximum operating pressure, an ultimate pressure of three times the maximum pressure, and a negative pressure of approximately one atmosphere. A fuel resistance test similar to that specified in MIL-F-8615 should be conducted.

h. Contaminated fuel. This requirement should be included because it is not always possible to keep fuel from becoming contaminated. A typical contaminant for test purposes is listed in MIL-F-8615.

i. Flame. Some transmitters may be required to withstand a flaming environment, particularly when they are mounted on the engine. If a flame should occur around the transmitter, it is essential that there be no damage that could result in leakage. Typical limits for this test are 1093 degrees C flame temperature for a period of five minutes. Depending upon the engine operation, fuel may be flowing or static at a particular pressure. Data from the airframe manufacturer may be required to complete this requirement.

j. Excessive and reverse flow. This requirement may be necessary on some aircraft depending upon how and where the fuel flow transmitter is plumbed into the fuel system. In some installations fuel flow rates may exceed the maximum specified in certain instances when fuel is being transferred from one tank to another through the transmitter. Reverse flow may be required during refueling operations.

REQUIREMENT LESSONS LEARNED (A.8)

Past experience has shown that certain materials are not well suited for use in fuel flow transmitters when they come in contact with fuels. Most plastics are unstable and can be affected by fuel additives; magnesium alloys are highly corrosive and react to any moisture in the fuel. Magnesium protective coatings have not proven effective over long periods because of scratches and thin spots in the coatings. Copper alloys and cadmium plating have been found to be attacked by many fuel additives, and copper salts are detrimental to engine oil which could become contaminated through the fuel in the engine. These materials should be prohibited. Fuel seals should be in accordance with MIL-STD-I587.

Fuel flow transmitters are mounted on the engine or airframe. The transmitter should be mounted at a slight angle with the outlet higher in order to purge air from the transmitter. Sharp bends in the inlet and outlet plumbing shall be avoided. This causes turbulence in the fuel and can produce erratic fuel flow measurement. End fittings may be "0" ring clamp-type, screw-on, or flange-type. Mounting designs must take into account plumbing expansion and contraction and vibration and temperature when mounted on the engine.

A.9 Fuel savings advisory system (FSAS).
The fuel savings advisory system shall display optimum flight profiles for minimum fuel consumption. The system shall be compatible with the aircraft and the missions to be accomplished. The following characteristics shall be included in the system for display to the aircrew: ________________________.

REQUIREMENT RATIONALE (A.9)

The Air Force has strong motivation to consider techniques for fuel conservation. Fuel costs continue to increase, and projected cost increases make fuel conservation even more important.

REQUIREMENT GUIDANCE (A.9)

The FSAS uses a technology which offers the potential for achieving significant fuel savings through the use of fuel minimizing-optimum flight path and throttle control laws. These control laws are designed to enable a pilot or an automatic flight control/autothrottle system to regulate an aircraft's kinetic and potential energy so that a minimum amount of fuel is expended while meeting the mission objectives. The FSAS should demonstrate mission fuel savings while considering the variability of aircraft performance, the current atmospheric conditions, and the existing air traffic control procedures.

Quantitative fuel savings should be in the range of 3-5 percent with the use of an FSAS as opposed to conventional flying procedures. The system is applicable to both current aircraft as well as future aircraft and offers a rapid return on initial investment costs through fuel savings. A secondary benefit of the FSAS is that it will lessen the flightcrew member's workload by relieving him (them) of the necessity to frequently calculate the aircraft's best altitude and airspeed from the flight manual charts. A typical FSAS is described in Exhibit ASD/ENAID-79-1, Revision 1.

A baseline system would consist of a computer and a display unit. The addition of EPR and IAS/Mach indicators with manual or remotely adjustable cursors will improve the usability of the system. Integrating the system into an aircraft's automatic flight control system and an auto-throttle system will further improve the usability and also provide additional fuel savings through more precise control of the aircraft flight. If an aircraft has autopilot and autothrottle systems available, it is advisable to integrate them into the FSAS control loop, as this will result in about 1 percent fuel economy improvement. Furthermore, depending on the type of equipment available on an aircraft, dedicated FSAS equipment may not be required. As an example, an existing digital computer with spare capability can be utilized to perform the computations or an existing display can be utilized to display the FSAS functions.

REQUIREMENT LESSONS LEARNED (A.9)

Flight tests on C-141, B-52, and KC-135 aircraft have confirmed that fuel savings of approximately 3 percent can be realized if an FSAS is used.

A.10 Fuel quantity system.
The fuel quantity gaging system shall indicate the amount of fuel in ______________________. The system shall measure and display the fuel quantity in ______________________ (units) and shall be in accordance with ______________________.

REQUIREMENT RATIONALE (A.10)

The fuel quantity readings are needed by the aircrew member to plan the length of his mission, to control the center of gravity of the aircraft, and to insure that sufficient fuel reserves exist to insure a safe return to base. It also is used as an input to some fuel savings advisory systems.

REQUIREMENT GUIDANCE (A.10)

The fuel quantity gaging system for use on Air Force aircraft shall measure and indicate the fuel quantity in pounds or kilograms. Most gaging systems are of the capacitance type that sense changes in the dielectric constant of the fuel/air mixture between the cylinders of the capacitance probes brought upon by raising or lowering the fuel level. Compensation is provided to correct for varying tank configurations.

The following items should be considered and specified for fuel quantity measuring systems.

a. Range. It is important to measure fuel from full to as near empty as possible. If a large unmeasurable amount of fuel exists, it will rob the aircraft of some of its potential range and apply as a weight penalty.

b. Accuracy. The readings must be most accurate when the fuel tanks are near empty to insure sufficient fuel to return to base. Typical accuracies are Class I, MIL-G-26988, ± 4 percent of indication in addition to ± 2 percent of full scale, for older aircraft. Most newer systems specify Class II, ± 2 percent of indication added to ± 0.75 percent of full scale. In rare instances where fuel quantity is extremely critical and is needed to control the center of gravity of the aircraft, such as the B-1 system, a tighter tolerance is used. That tolerance is usually Class III, ± 1 percent of indication and ± 0.5 of full scale. This accuracy requires an attitude correction computer as part of the system and will, therefore, result in much more expense. New weapon systems should be encouraged to utilize Class II systems whenever possible.

c. Provisions. The fuel gage should provide an adjustable signal to close the refuel valves for intermediate fuel loads.

d. Display. Fuel quantity displays take many different forms, including round dial, numeric readout, vertical scale, etc. The configuration of the air vehicle will dictate the best display. In general, a display will be included for each tank. A display of total fuel is also usually provided.

e. Tank units. The aircraft fuels and all their additives (including anti-static additives) and water that condenses out in the tanks should not detrimentally affect the life, reliability, and accuracy of the tank units.

f. Materials. Aircraft fuels and additives should not affect the materials used to construct the tank units so that the fuel gaging system accuracy is not adversely affected and fuel is not contaminated.

g. Installation and calibration: Guidance for installation and calibration of the fuel quantity gaging system is contained in MIL-G-7940 and MIL-F-87154.

REQUIREMENT LESSONS LEARNED (A.10)

It has been found that tank units should be top-mounted and externally accessible wherever possible for system maintenance.

The use of fuel additives, alternate fuels, and contaminated fuels is causing some concern about the adequacy of capacitance-type gaging systems. These factors should be investigated when specifying a capacitance system.

A.11 Horizontal situation indicator (HSI).
The HSI shall provide a pictorial display of the navigational relationship of the aircraft to the earth, including other information as follows: ________________________. It shall be compatible with ________________________.

REQUIREMENT RATIONALE (A.11)

The HSI is usually the pilot's primary heading reference. It is a navigation instrument whose display was developed to aid pilots in intercepting TACAN or VOR radials, but it is also used with other navigation methods such as Area Nav and INS.

REQUIREMENT GUIDANCE (A.11)

The HSI shows the aircraft heading with respect to north (magnetic or true) and the aircraft position with respect to a selected ground station and a selected course to the ground station. The aircraft heading is shown on a compass card beneath a lubber line. The display also gives slant range and bearing to a selected ground station and allows the pilot to select a desired course toward the station. The HSI then shows the aircraft position with respect to this selected course. The pilot can select a desired heading which is shown by a marker on the outer edge of the compass card. TO-FROM information with respect to the selected ground station is shown in the center of the HSI. The HSI also has various failure warning flags. The following functional capabilities are considered to be the minimum necessary for an adequate HSI display:

a. Heading. The aircraft heading is the direction the aircraft is pointing. The actual direction of flight ("track") may be slightly different depending on crosswinds or aircraft control problems. The heading may be referenced to either magnetic north or true north depending on the directional reference source. Usually, a directional gyro output is referenced to magnetic north while an INS output is referenced to true north. The accuracy of the azimuth card (or compass card) is usually specified as 1 degree minimum, which is readily achieved in any well-designed instrument and is about the limit of readability on a normal azimuth card with 5 degrees between markings. For the larger HSIs (4 x 5 or 5 x 5), an accuracy of 1/2 degree can be specified with the azimuth card marking spaced at 2 degrees. The heading input signal for the HSI depends upon the directional reference source which probably will have a synchro signal output but which may have a digital output, such as with a MIL-STD-1553 data bus.

b. Command heading. The command heading is a heading the pilot wishes to fly from 0 to 359 degrees and which can be set with a knob on the HSI or can be set remotely, usually by a second HSI.

c. Heading marker. A heading marker is set around the outside edge of the azimuth ring to show the command heading which has been selected. The heading marker (also called heading "bug" or "Captain's Bars") is set manually or remotely depending on the HSI mode (master or slave), which is controlled by the external pin connections. In a two-place cockpit, one HSI will be the master and one the slave so that both HSIs will display the same command heading. Each HSI should be capable of acting as either the master (called "remote device" in specification) or the slave. The signal may be synchro or digital. When choosing a signal format, consideration should be given to the signal format of any equipment which interfaces with the command heading display of the HSI.

d. Command heading rate and accuracy. The maximum rate of change for command heading is usually specified to be 60 degrees per second, as *this is about the maximum rate at which the pilot can* manually set the master HSI. While the minimum rate of change is 0 degree per second, the lowest measured rate of change is usually 1-1/2 degrees per second, which corresponds to a 4-minute turn.

e. *Remote heading signal. When the HSI is operating in the* SLAVED mode, it must receive a command heading signal for a remote source. If no signal is available, the heading marker may rotate continuously around the azimuth card. When an HSI is in the SLAVED mode, rotating the set knob may temporarily move the heading marker; however, the marker must return to the heading of the remote device to preclude having separate command heading values on the two HSIs. After being set manually (only in the master mode) or remotely, the marker must not move with respect to the azimuth card even if the azimuth card is rotating. The accuracy will normally be specified as 1 degree with an azimuth card having 5 degree marking or 1/2 degree with a card having 2 degree markings.

f. Command course. The command course is a heading the pilot wishes to fly toward a specific point, usually toward a selected TACAN station. The course can be set manually with a knob on the HSI or it can be set remotely, usually by a second HSI.

g. Course marker. A course arrow (marker) is set to the desired heading on the inside edge of the azimuth card to correspond with the course selected. The course arrow may be set manually or remotely depending on the HSI mode (master or slave) which is controlled by the external pin connections. In a two-place cockpit, one HSI will be the master and one the so that both HSIs will display the same command course. Each HSI will normally be capable of acting as either the master or the slave. The signal may be synchro or digital. When choosing a signal format, consideration should be given to the signal format of any equipment which interfaces with the command course display of the HSI.

h. Course readout. In order to aid the pilot in rapidly and accurately selecting a command course, a digital course readout is provided in the upper-right-hand corner of the HSI face.

i. Course rate and accuracy. The maximum rate of change for the course arrow is usually specified to be 60 degrees per second for the same reason as in the command heading. Likewise, the lowest measured rate is usually 1-1/2 degree per second. The accuracy is usually specified as 1 degree if the azimuth card has 5 degree marking and 1/2 degree if the card has 2 degree markings.

j. Remote course signal. In the slaved mode, the HSI must receive a remote course signal to preclude continuous rotation of the course arrow. A rotation of the course set knob on the slaved HSI may cause a temporary movement of the course arrow; however, the arrow must immediately return to the value set by the remote device to *preclude erroneous readings. After being set to a given value, the* course arrow must not move with respect to the azimuth card unless reset to a new command course. The accuracy is usually specified as 1 degree if the azimuth card has 5 degree markings or 1/2 degree if the card has 2 degree markings.

k. Course deviation bar. The command course is a specific direction toward a specific point and can be represented by a signal line on a map or by an imaginary line on the earth. If the aircraft is flying on course, it should be flying directly above and along this imaginary line. The deviation bar (D bar) shows the relationship of the aircraft to this imaginary line, which represents a command course. If the miniature airplane in the HSI is to the right of the deviation bar, then the actual aircraft is to the right of its commanded course. The impedance of the D bar input is usually specified as 1000 ohms for compatibility with existing equipment. Likewise, the current required for one-dot displacement usually specified to be 75 uA, with two dots requiring 150 uA. In most aircraft one dot on the D bar represents 5 degrees off course with two dots for 10 degrees. One degree off course is defined as a 1 degree difference between the command course and the bearing to the selected station.

l. Deviation bar alarm flag. The primary purpose of the deviation bar alarm flag is to indicate whether the deviation bar input signal is usable or not; however, when in the TACAN mode, it also shows whether the bearing signal is usable or not. The suppress zero-type of meter movement holds the flag tightly against its stop until the input current is a substantial fraction (about 1/3) of the maximum rated current. This prevents the flag from moving off its stop during high vibration or high "g" loading environments. In order to be compatible with existing equipment, the flag is normally required to leave its stop at no less than 180 uA and be fully out of view at not more than 245 uA. For reasons of compatibility, the input impedance is usually required to be 1000 ohms. With a digital interface the flag operation may be a function of a status bit rather than a function of an input current.

m. TO-FROM arrow. The TO-FROM arrow is used in making TACAN or VOR intercepts. The arrow shows whether the aircraft would fly toward or away from the station if the selected course were intercepted and flown. The signal is usually generated in the TACAN or VOR coupler; however, the HSI can be designed to generate the signal internally if the TACAN or VOR coupler is to be deleted. For compatibility with existing TACAN and VOR couplers, the TO-FROM arrow should have 200 ohms input impedance and should come into view with +225 uA.

n. Display movement. The central portion of the display contains all of the information pertaining to the selected course and rotates as a unit with the azimuth card in order to present the desired information in a usable and coherent manner.

o. Bearing pointer. The bearing pointer indicates the direction toward a selected radio station or other target. Because a pilot may wish to track a TACAN station plus another radio station in the direction finding (DF) mode or may need to find his position by triangulation, it is desirable to have two bearing pointers on the HSI. If this is not possible because of size constraints or other reasons, one bearing is considered to be the minimum acceptable. The maximum rate of change for the bearing pointer is usually specified to be 60 degrees per second, as this is adequate for navigation purposes and is relatively easy to achieve. It also keeps the test requirements uniform when compared to the other servos on the HSI. The lowest measured rate of change for the bearing pointer is usually taken to be 1-1/2 degrees per second, as this corresponds to a 4-minute turn. This low rate is often more difficult to achieve satisfactorily because of problems with jumpiness and erratic movement at the low rates of movement. The accuracy is usually specified as 1 degree if the azimuth card has 5 degree markings and 1/2 degree if the card has 2 degree markings.

p. Distance display. The distance (range) to a selected station is presented in the upper-left-hand corner of the HSI in order to standardize the display features. The distance is usually the slant range but could be some other value received from a computer. The normal display consists of three digits, each operated by a separate synchro receiver with separate three-wire inputs. The display may also have a separately controlled thousands' flag to increase the range of the display from 999 to 1999. If the distance display is intended to interface only with a TACAN, a range of 999 miles would be sufficient. The distance display can be designed with a digital interface, for use with a digital TACAN, or with a digital multiplex bus; however, the range of the display will still be a function of the interfacing equipment which supplies the distance signal. If the signal is available to accuracies of one-tenth of a mile, it would be advantageous to display to that accuracy. This can be done by adding an additional digit or by using a movable decimal point. If a movable decimal point is used, the typical accuracy would be one-tenth of a mile from 0 to 999 miles and one mile from 100 to 999 miles.

A.12 Hydraulic pressure indicator and sensor.
The hydraulic pressure indicator is used in conjunction with a hydraulic pressure sensor and is used to display pressure of each hydraulic system on the aircraft. The following requirements apply:

REQUIREMENT RATIONALE (A.12)

Hydraulic pressure measurement is used to monitor the hydraulic systems on the aircraft. Hydraulic pressure measurement is necessary to insure operational and functional system capability on those aircraft which use hydraulic power for flight control, landing gear actuation, etc.

REQUIREMENT GUIDANCE (A.12)

Most of the hydraulic pressure measurement systems in current use are of the basic synchro type.

The following requirements should be specified.

a. Range. Most of the hydraulic pressure systems in Air Force aircraft require a 0-4000 psi range. A few aircraft have higher hydraulic pressure systems where a 0-5000 psi range is required. The vehicle system requirement will dictate the range.

b. Accuracy. The accuracy of the hydraulic pressure indicating system is approximately 5.0 percent of full-scale reading. The indicator and transmitter accuracies are approximately 2.5 percent of full-scale reading and are fairly constant over the entire range. Accuracies at high and low temperatures will be greater than at room temperature and will have to be specified accordingly depending upon the temperature extremes expected and the accuracies required.

c. Response. Requirement of hydraulic pressure indication response time may be required for two reasons: (1) to follow rapidly dropping hydraulic pressure or system fluctuations and (2) to follow not-so-rapidly dropping hydraulic pressure or system fluctuation so as to cause oscillations or erroneous readings. Typical response time of a pressure drop from 4000 psi to 500 psi is 1 second to 3 seconds for the transmitter and not more than 2 seconds for indicator response time.

d. Display. Hydraulic pressure displays are typically installed in 1-inch round dial clamp-mounted cases per MS-33639. The scale should be oriented so that the normal hydraulic pressure indication is positioned in the 11 o'clock to 1 o'clock position. Any other display may be used depending upon panel space and application.

e. Transmitter output signal. Depending upon the indicator, the transmitter may use a synchro signal, voltage output, or other analog signal. If a digital signal is specified, it shall be compatible with MIL-STD-1553 or with ARINC standards depending upon end usage.

f. Overpressure. The transmitters are usually required to withstand an operating overpressure of 1000 psi (500 psi applied) without degrading the performance. The 1000 psi overpressure is considered adequate to meet the most severe overpressure fluctuations in the hydraulic pressure system. An upper limit of 3500 psi over max normal (7500 psi applied) is usually specified for rupture or leakage tests. Some loss of performance or permanent damage is allowed after this test.

REQUIREMENT LESSONS LEARNED (A.12)

The transmitter should be mounted as near to the hydraulic fluid reservoir as possible. This minimizes the possibility of line ruptures and leakage due to exposure of long lines to excessive vibration or wear against sharp edges or protuberances. Pipe connections to transmitters are prone to leakage. Fittings per MS-36649 are preferred.

A.13 Magnetic compass.
The magnetic compass provides an indication of aircraft magnetic heading for use as a backup heading reference and for cross-checking the primary heading reference system. The following requirements shall apply: __________________________.

REQUIREMENT RATIONALE (A.13)

The magnetic compass indicates the heading of the aircraft with respect to magnetic north. It requires no electrical power for operation other than for lighting. The purpose of the magnetic compass is for a heading source for emergency use and for cross-checking other aircraft heading systems. Most aircraft require a magnetic compass as an emergency heading source.

REQUIREMENT GUIDANCE (A.13)

The following requirements apply when specifying a typical magnetic compass:

a. Display. The compass mechanization typically consists of two bar magnets attached to a pivoted compass card and float. This mechanism is housed within a case full of fluid in accordance with MIL-L-5020. An expansion unit is required to allow for liquid expansion and contraction with temperature changes. A lubber line is installed such that parallax errors are minimum when reading heading from the compass card. The compass card is marked in 5 degree increments with each 30 degree increment labeled with the appropriate heading angle and cardinal heading angle and cardinal headings labeled with N, S, E, and W. Increments larger than 5 degrees should not be used as readability errors would become excessive.

b. Compensator. The magnetic compass must be equipped with a compensator for removing errors in north-south and east-west headings due to aircraft magnetic fields. The compensator consists of two permanent magnets that are manually adjustable. A zero index mark is required to indicate the adjustment position where the compensator magnets exert zero effect on the indicator. The range of the compensator must be sufficient to remove errors due to the particular aircraft's magnetic field. Typical ranges that have proven suitable for any aircraft application are between 30 degrees and 40 degrees.

c. Bubble visibility. Air bubbles should not be visible in the usable attitude range of the magnetic compass. This range is typically no more than 18 degrees in pitch. Steeper pitch angels result in larger errors which make the compass unusable.

d. Friction error. Typically, a friction error of 1 degree maximum has proven acceptable and is easily met.

e. Balance. The compass card must be balanced to provide a readable and accurate display. Deviation of 1 degree between the compass card plane and the horizontal plane is generally required and has proven to be easily met.

f. Compass error without compensation. The accuracy of the standby compass is typically within ±1.0 degree without compensators attached. This requirement has generally proven acceptable.

g. Attitude range. Pitch attitudes of ±10 degrees should cause no more than 2 degrees change in compass indication. Pitch or roll attitudes of ±18 degrees should cause no more than 5 degrees change in indication. These attitude errors are characteristic of the typical compass mechanization and should easily be met.

h. Compass swing. Each aircraft standby compass must be calibrated through a compass swing when the compass is first installed, when it is replaced, or when its errors become excessive. MIL-STD-765 defines the magnetic field conditions at the swing site required to perform the compass swing. In addition, it provides the general requirements for a number of acceptable compass swing procedures which include the following: compass rose procedure, sighting compass procedure, magnetic method using a transit, comparison swings, and air swings. Compliance with MIL-STD-765 is a requirement that should be imposed on the airframe contractor to insure an acceptable compass calibration.

REQUIREMENT LESSONS LEARNED (A.13)

When the magnetic compass is installed in an aircraft, its indications will be affected by magnetic fields in the aircraft such as those due to magnetic materials or lines carrying DC. To provide accurate indications the compass must be located to minimize the effect of aircraft magnetic fields. MIL-C- 7762 defines the requirements for determining the acceptability of a selected location. MIL-C-7762 accomplishes this by specification of the maximum allowable errors due to aircraft climb and glide attitudes, movable and removable magnetic parts, engine operation, landing gear effect, effect of continuously operated circuits, effect of variable circuits, and specification of the maximum allowable uncompensated and compensated compass deviations. Test procedures are defined for measuring these various effects. The requirements of MIL-C-7762 for direct indicating compasses should be imposed on the airframe contractor to insure that errors due to the compass installation can be compensated for and to insure residual errors after compensation are not excessive.

A.14 Engine oil quantity indicating system.
The oil quantity indicator shall receive signals from an oil quantity sensor and display to the aircrew the oil quantity in ____________________ (units) remaining in each tank associated with each engine. The characteristics of the system shall be as follows: ____________________.

REQUIREMENT RATIONALE (A.14)

All aircraft engines require a continuous flow of oil for lubrication and cooling. Each engine is usually fitted with an oil tank, and it is important to know the quantity of oil in each tank. Knowing the oil quantity and the rate of usage as determined by the oil quantity gage, the duration of flight can be determined. This is important in case of an oil leak or excessive oil consumption by a particular engine.

REQUIREMENT GUIDANCE

There are several types of oil quantity systems available. Technical Report ASD-TR-74-39 provides a comprehensive review of these systems and some of the factors that should be considered when specifying an oil quantity system.

The following requirements must be addressed when specifying an oil quantity measuring system:

a. Units of measurement. The engine oil quantity indicating system should display volumetric quantity rather than weight of oil because oil consumption is discussed in terms of quarts or liters per hour. Oil is added one quart at a time, as it is procured only in quart cans to avoid the possibility of an open can being left for future use and becoming contaminated.

b. Range. Full should correspond to minimum oil level which is about 20 percent less than actual tank capacity to allow for oil expansion. Empty should correspond to minimum usable oil in the tank in the event that the tank is designed so that an unusable amount of oil may remain in the tank.

c. Accuracy. There is a tendency to require greater accuracy than is actually needed. Care should be taken in "profiling" the output to the tank it would be if it were mounted in a fully loaded aircraft flying straight and level. This will normally be a different angle than the tank would assume when the aircraft is parked on the ramp.

d. Response time. Rapid response time is not required and is not desirable. Too rapid response time will result in much pointer fluctuation due to oil slosh. Ten to fifteen seconds for a full-scale change is usually adequate.

e. Display. Oil quantity displays can be in many different forms. On large aircraft the oil quantity display is normally a 2-inch diameter round dial display. On fighter-type aircraft, a dual-level system may be considered consisting of two lights in the cockpit for each engine oil tank. One light would indicate that the 1/2 point has been reached; the second light would indicate that the 1/4 point has been reached.

f. Prohibited materials. Because oil samples are used for diagnostic purposes, there are several materials which may not be permitted to come in contact with the oil. Copper is one of these materials, and there are others. Since the list is changing, it should be consulted prior to the issuing of a specification.

REQUIREMENT LESSONS LEARNED

Many oil quantity gaging systems use floats. Historically, the float has always been considered to be a very simple device to build when in reality many failures in several different systems were the result of faulty float design. The float must be designed to withstand two types of pressure cycles. One is the larger change of about 6-8 lbs/sq inch which occurs a few times in a flight due to initial startup and a altitude changes. The other cycle is a small change that occurs many times in a flight due to temperature changes in the tank and throttle movement. If a metal float is not properly designed, the sides of the float will move with the pressure changes that will cause fatigue and/or work-hardening which will result in a crack which will sink the float. Nonmetallic floats have encountered problems due to the long-term adverse effects of MIL-L-7808 and MIL-L-23699 oils. Consideration of a metallic float with internal structural honeycomb is recommended.

All but the very shortest tank probe should be retained at each end. A good method is to use a straight-sided socket in the bottom of the tank with a mating part with a groove cut into it mounted on the bottom of the probe. An "O" ring on the groove will provide for differential expansion and tank tolerance variations. The "O" ring is the only part of the probe which comes into contact with the socket. Generally, probes longer than 15 cm should be restrained at each end to prevent fatigue failure of the probe and/or of the tank around the mounting flange.

Nucleonic oil quantity measuring systems should be avoided. Most of these types of systems have been removed from USAF aircraft. The acquisition cost is high, as is the maintenance cost. The systems must be recalibrated every 6 months due to the decay of the radioactive source and it is dangerous for personnel to work around the radioactive source for more than 15 minutes at a time.

A.15 Oil pressure indicating system.
The oil pressure indicator shall display the pressure of the engine oil to each engine in ____________________ (units) using signals from a remote sensor. The oil pressure sensor shall measure the pressure of the oil supplied to each engine and provide a signal proportional to the pressure for use by a display or other equipment. The following requirements shall apply:

____________________.

REQUIREMENT RATIONALE (A.15)

Engine oil pressure is of vital importance to the operation of any aircraft engine. If the oil pressure drops below certain limits, that engine must be shut down or it will be destroyed.

REQUIREMENT GUIDANCE

Each engine oil system is to be provided with an oil pressure transmitter and an associated pressure indicator in the crew station. Oil pressure readings are calibrated in pounds per square inch (psi) in the English system and kilopascals (kPa) in the metric system. Indicator dials are to be provided with colored range markings in accordance with T.O. 5-1-2 and STANAG 3436.

The following requirements should be specified for oil pressure indicating systems:

a. Range. Most oil pressure systems for engine bearing lubrication on Air Force aircraft operate in the 0-100 psi range. There are systems that operate in the 0-200 psi and 0-500 psi range.

b. Accuracy. The accuracy of the oil pressure indicating system is approximately 4.0 percent of full scale reading. The indicator has an accuracy of approximately 1.5 percent, and the transmitter has an accuracy of approximately 2.5 percent of full-scale reading and are fairly constant over the entire range. Accuracies at high and low temperatures will be greater than at room temperature and will have to be specified accordingly depending upon the temperature extremes expected and the accuracies required.

c. Response. Requirement of oil pressure indication response time may be required for two reasons: (1) to respond in a reasonably short time under extreme cold temperatures on engine start and (2) to respond not too rapidly to cause fluctuations or excessive oscillations. Typical response time at cold temperature shall be 1 second to 4 seconds with a pressure change from 100 psi to 10 psi for the transmitter and not more than 1 seconds for the indicator.

d. Display. Oil pressure displays are typically installed in 1-inch or 2-inch round dial clamp-mounted cases per MS33639. The scale should be oriented so that the normal oil pressure indication is approximately at the 9 o'clock position. Other displays may be used.

e. Transmitter. The oil pressure transmitter must be compatible with the indicator or display intended for use. The output signal format may be analog or digital. Synchros and variable reluctance-types are commonly used. If a digital signal is specified, it shall be compatible with MIL-STD-1553 or with ARINC standards depending upon user preference and end use.

f. Overpressure. The transmitter must withstand an overpressure and still operate within specification tolerance requirements. For most aircraft using 0-100 psi oil pressure systems on overpressure of 200 psi (300 psi applied) is considered adequate for covering any severe overpressure fluctuations occurring under most conditions.

g. Burst pressure. An overpressure of 400 psi (500 psi applied) is usually specified for the transmitter to withstand without rupture or leakage to the pressure-sensing element. This test should be run at 70 degrees F with pressure applied to the input oil pressure port.

h. Mounting. The transmitter should be mounted on the engine although it can be and is mounted on the airframe of some aircraft. Mounting of the transmitter on the engine eliminates extra fittings and oil lines and reduces the chances of oil line rupture on leakage.

i. Mounting torque. A mounting torque test is usually specified for the transmitter to insure that the case of the transmitter can withstand normal torque forces applied during installation without causing distortion or other failures affecting the accuracy.

j. Temperature. Temperature requirements for oil pressure transmitters are greater than most other equipment. Typical temperatures usually specified are from -54 degrees C to +177 degrees C.

k. Materials. As in the case of oil quantity gaging systems, copper and alloys of copper are not to be used in contact with engine oil.

REQUIREMENT LESSONS LEARNED

In the past, many oil pressure transmitters used silicone fluid for damping. Very minute quantities of silicone fluid intermixing with the lubricating engine oil results in a serious foaming problem causing loss of oil pressure and bearing lubrication. This problem has been encountered previously where the oil pressure sensing element in the transmitter ruptured or failed allowing the silicone fluid to mix with the engine lubricating oil. The use of silicone fluids in transmitters should be prohibited.

A.16 Position indicating system.
The position indicator system is used to indicate the position of certain elements of the aircraft such as flaps, wings (sweep), pitch trim, nozzle, etc. It shall meet the following requirements: ____________________.

REQUIREMENT RATIONALE (A.16)

To provide visual feedback, it is considered necessary to provide a position indicator for any control surface that cannot be seen by the aircrew.

REQUIREMENT GUIDANCE

Generally, surface position indicators do not have to be highly accurate devices except for wing sweep angle. They are generally used to verify that a surface is moving in accordance with a command. Nozzle position indicator systems are used primarily to assure the pilot that the propulsive system is functioning properly. It is not used as a power setting device.

The following factors must be considered when specifying these systems:

a. Display. Position displays are usually 2-inch diameter instruments. The use of symbolic displays consisting of a miniature aircraft or wing cross section should be considered. The effect of control surface trim can be displayed on the miniature aircraft and the position of life control devices, such as spoilers and flaps, can be displayed on the wing cross section.

b. Range. Surface position is usually displayed in degrees. Nozzle position is generally displayed in percent of full open.

c. Accuracy. Surface position is generally displayed to an accuracy of +3 degrees of transmitter shaft. Pitch trim indication should be displayed somewhat more accurately. The rigging of the linkage between the transmitter and the control surface can be a source of considerable error, and tolerances should be determined for technical order use.

d. Response. The indication should be capable of moving slightly faster than the surface to which it is attached. Since engine nozzle movement can be extremely rapid, it may not be possible for the indication to follow it.

e. Torque. The torque required to rotate the transmitter should be checked at temperature extremes to insure that differential expansion will not cause internal binding. The transmitter for either an engine nozzle or wing surface can be exposed to a very wide temperature change very rapidly.

f. Anti-freeze-up. Position transmitters for slats and flaps are located in the wing and may be exposed when the surface is extended. In rain they may be exposed to a lot of water which can freeze as the aircraft climbs to altitude. An anti-freeze-up test should be required on transmitters subject to rain and subsequent freezing temperatures.

REQUIREMENT LESSONS LEARNED

It has been found that position transmitters exposed to rain should be as well sealed as possible. The use of drain holes has been detrimental because rain is often driven into the transmitter through the drain holes and is prevented from draining due to air flow.

A.17 Tachometer indicator system.
The tachometer display shall indicate the rotational speed of ____________________ (units). It shall operate using signals from ____________________.

REQUIREMENT RATIONALE (A.17)

Engine rpm is an important parameter which must be displayed to the aircrew for safety and performance reasons. It is used during engine starting and all portions of flight.

REQUIREMENT GUIDANCE

The rpm of gas turbine engines is always displayed as a percent. This is because the numbers tend to be high and vary greatly with the diameter of the engine. For some engines, rpm is the main power parameter. With few exceptions, all USAF aircraft and commercial airlines (and helicopters) use the standard tachometer system. The standard system consists of an engine-mounted tachometer generator and a 2-inch diameter indicator. Basically, the standard system consists of an electric AC 3-phase generator which drives a 3-phase synchronous motor in the indicator. The synchronous motor rotates several magnets within a copper drag cup. The standard tachometer generator consists of a 3-phase winding with a 2-pole permanent magnetic rotating inside the winding. The tachometer generator provides both the signal and the electrical power to drive the indicator. The standard indicator has a four (4) pole permanent magnetic rotor turning in a field, wound to accept the 3-phase output of the generator. The indicator rotor synchronizes at one-half (1/2) of the generator rotor speed. Therefore, the rpm signal is transmitted by the frequency of the 3-phase electrical signal, not the voltage level as is commonly believed. The power (1/3 amp at 21 volts) generated by the generator drives the motor in the indicator. The only external power required is for the indicator lights. A tachometer system should be provided for each engine. On dual spool engines--notably large turbofan engines--a tachometer system may be provided for each spool. The system consists of an engine-mounted transmitter and remote display. Engine rpm shall be measured and displayed as a percentage of the maximum permissible rpm at the maximum continuous non afterburning power setting. On helicopters, the rotor transmitter may be mounted on the transmission. Rotor speed will be displayed as actual rpm. The rpm of reciprocating engines will be displayed as actual rpm.

The following factors must be considered when specifying tachometer systems:

a. Range. The display range for gas turbine engines should be from 0 to 110 percent to provide for engine growth through rerating. Propeller and helicopter rotor speeds shall be displayed in actual rpm.

b. Accuracy. Highest accuracy should be required in the 80 percent to 105 percent range. To require an accuracy of plus and minus 0.5 percent in this range is reasonable; even greater accuracy may be desirable. The accuracy below 80 percent could be reduced to plus and minus 2.0 percent or even plus and minus 3.0 percent. At the lower ranges, the tachometer is used during starting to observe the rate of increase of speed to guard against hot starts and hung starts. In the higher ranges, technical orders generally prescribe limits or operating points to one-tenth of a percent (0.1 percent). At temperature extremes, particularly low temperatures, the accuracy tolerances should be relaxed as much as practicable. In some designs, a reduction of low temperature accuracy permits the use of larger amounts of lubricant.

c. Response. The tachometer system should be able to travel up scale slightly faster than the engine can accelerate to 100 percent rpm. Particular attention should be paid to the area between 80 percent and 100 percent rpm to insure that the tachometer indication can keep up with the engine acceleration in this area. This is so that the operator will have the capability of preventing an overspeed in the event of a governor failure.

d. Starting and synchronous operation. In some cases, the operator may want to measure acceleration or coast-down time or perform some operation that can only be done when the engine is not turning. Therefore, the tachometer system should start functioning at a very low rpm, such as 2.5 percent, and with decreasing speed, continue to function down to a low rpm.

e. Display. The display must have the capability of being read to within 0.5 percent. This is usually accomplished using an expanded scale in the critical regions or by the use of a vernier subdial. Displays can be the 2-inch round dial type, vertical scale, or other depending upon user preference, cost considerations, etc.

f. Transmitter. Most systems utilize the standard transmitter which mounts on the standard drive pad located on the engine accessory case. If a magnetic pickup operating from a gear is used, electrical shielding should be considered. In the past, this type of transmitter has proven troublesome because the coil tended to act as an antenna. Efforts to induce and detect eddy currents in titanium fan blades as they passed a sensor have proven less than successful because of clearance variation with wear and temperature changes. References to tachometer indicators can be found in STANAG-3691, and several military specifications found listed in the DOD index of specifications and standards under indicator, tachometer, and generator, tachometer.

REQUIREMENT LESSONS LEARNED

See paragraph A.17 - "f" above.

A.18 Thrust computing system (TCS).

The system shall display actual gross thrust divided by reference thrust as a percentage. Rerating of the engine shall not require changes to the gross thrust computation algorithm. The system will receive information (pressures, temperatures, etc.) from the following aircraft systems: ________________. The system will provide information to the following aircraft systems: ________________.

REQUIREMENT RATIONALE (A.18)

The measurement of engine thrust has been a long sought-after achievement. Only recently has it been possible to measure airborne thrust, the most important parameter as far as air vehicle takeoff and performance is concerned. The TCS should be considered for use on any new air vehicle using turbojet, turbofan, or afterburning turbojet and turbofan engines.

REQUIREMENT GUIDANCE (A.18)

The TCS computes the actual gross thrust (in pounds) being produced and the percentage (based on military power, non afterburning) of available thrust that is actually being delivered. The TCS is operable on the ground and in all flight modes. While the TCS is applicable to any turbojet or turbofan engine, greatest benefits can be accrued by applying it to variable nozzle engines. On variable nozzle engines, the TCS provides performance information not available from other engine instrumentation. Some potential benefits of utilizing the TCS are as follows:

(1) Single instrument, quickly interpreted.

(2) Provides immediate quantitative assessment of malfunction, deterioration, icing, battle damage.

(3) Confirms proper operation of complete propulsion system prior to takeoff.

(4) Reduces unsubstantiated pilot squawks.

(5) Allows more accurate engine trimming which will reduce costs.

(6) Input to energy maneuverability system, flight recorder, etc.

(7) Unchanging performance standard built into each system.

When specifying a TCS, the following requirements must be considered:

a. Range. The percent system should be designed so that 100 percent is equivalent to full military power (non afterburning for afterburning engines). In this usage, the term "full military power" means the maximum non afterburning thrust level that the engine can maintain continuously in an operational situation. On an afterburning engine, whenever the afterburner is lit, the percent display will indicate over 100 percent.

b. Accuracy. To be useful, the system should have a gross thrust error of not more than plus and minus 2.5 percent of the point. The accuracy should be greater at the full military power point, especially if the TCS is to be used for engine trimming. The accuracy of the percent function will necessarily be no better than the accuracy of the gross thrust readout.

c. Response. The system should be capable of changing indication slightly faster than the engine is capable of changing the amount of thrust that it is producing.

d. Sensitivity. The system should be capable of responding to the minimum adjustment of the fuel control.

e. Interfaces. The system will interface with the central air data computer (CADC) and the engine pressure transducers. The CADC will provide ambient pressure and temperature information to the TCS as well as providing a MACH signal. The engine pressure transducers will provide inputs of total pressure behind the turbine, static pressure at the flame holder, and the static pressure at the entrance to the nozzle to the thrust computing algorithm. It is expected that the output of the TCS will operate a cockpit display, a go-no-go indication, play a part in any diagnostic or engine monitoring programs, and provide an input to future energy management or energy maneuverability systems.

f. Display. The display may take any convenient format suitable to the air vehicle. It is anticipated that the thrust display (percent thrust or gross thrust or both) will become the primary engine instrument, thus relegating the traditional engine instrument displays to an area of lesser importance.

REQUIREMENT LESSONS LEARNED (A.18)

It has been learned by AFLC that J85 engines can be successfully trimmed using a TCS system. The engines are experiencing longer life characteristics because the trimming is more accurately controlled toward the minimum allowable thrust range, thereby maintaining a more uniform, lower operating engine temperature.

A.19 Turn and slip display.
Turn and slip displays provide an indication of aircraft rate-of-turn and slip information. It shall have the following characteristics: ____________________.

REQUIREMENT RATIONALE (A.19)

The turn-and-slip display provides an indication of aircraft rate of turn and slip. It is sometimes considered as a standby indicator in event of failure of the attitude indicator.

REQUIREMENT GUIDANCE (A.19)

The turn needle can display either a standard two-minute turn for one-needle-width deflection or a four-minute turn for one-needle-width deflection depending on the mechanization of the indicator and system or rate gyro, sensing aircraft rate of turn. Most rate-of-turn displays are mechanized to display a four-minute turn for one-needle-width deflection. The slip indicator or inclinometer indicates aircraft slip or skid by means of a ball free to roll in a curved glass tube. This tube is filled with a colorless fluid which is normally alcohol to provide damping. The preferred color for the ball is white. However, if the slip indicator ball is smaller than 0.20 inches in diameter, a black ball is preferred. The reason for this is that black balls being metal are denser than the white ceramic balls, and as a result, the possibility of sticking is minimized. White ball slip indicators of less than 0.2 inches in diameter have generally proven unacceptable.

The following requirements apply:

a. Rate-of-turn display. The turn-rate display normally appears similar to that contained in MIL-I-7627.

b. Turn-pointer damping. The turn-pointer must have some damping to prevent pointer oscillation. A suitable damping factor of full-scale deflection from one to three seconds has been found to be satisfactory.

c. Turn-pointer accuracy. An accuracy of not more than plus and minus 7.5 percent of the input rate has been found adequate.

d. Slip display. The display of slip is mounted directly below the turn display and usually consists of a ball rolling in a curved glass tube as described above. At least half of the ball must be visible at all times. No part of an air bubble is to be visible in the tube.

e. Slip-indicator damping. The time for the slip ball to roll from the zero mark to the end of the tube should be not less than 0.2 seconds when the indicator is rapidly tipped to an angle of 24 degrees.

f. Full-scale deflecting. The slip ball should travel full scale when the indicator is tipped between 6 degrees and 12 degrees depending upon the sensitivity required for best aircraft control. The ball must travel freely from one end to the other with no sticking. Most of the requirements established for turn-and-slip indicators were generated through trial and error. Damping and sensitivity requirements were determined by flight tests and pilot opinion and have been found to be acceptable in most aircraft. STANAG 3322 outlines international agreements established for the indicator.

REQUIREMENT LESSONS LEARNED (A.19)

Since most turn-and-slip indicators were and are powered by 28V DC, the original designs used DC commutator motors to turn the gyro motors. The brushes used in DC motors are subject to wear and provide very low reliability. New designs specify the use of inverters and AC motors which greatly increase the reliability of this type of indicator.

Normally, turn-and-slip indicators are tested on level rate tables with no bank angles applied. This does not represent a true flight condition because there will always be some bank angle, depending upon airspeed, when the aircraft is turning. If very accurate turn-rate indications are required, it is recommended that the bank angle corresponding to the airspeed and rate of turn be applied when testing the indicator. This requirement would mean that the indicator would have to be designed for a certain airspeed. If this were done, the airspeed for which the indicator is intended should be marked on the case.

A.20 Warning system.
The warning system shall warn the aircrew of a dangerous situation or an impending dangerous condition using an aural tone and/or voice warning. A warning of the following conditions shall be provided: ____________________. The warning system shall have the following features: ____________________.

REQUIREMENT RATIONALE (A.20)

Warning signals are an inherent part of the operation of any aircraft. During heavy workload periods, the aircrew cannot monitor every system adequately and must be warned of a dangerous or an impending dangerous condition.

REQUIREMENT GUIDANCE (A.20)

A warning can be presented to the pilot by visual, aural, and/or tactile means. Recommendations concerning intensity, color, aural frequency, and repetition rates of the warnings involve considerable human factor considerations. AFSC DH 1-3 provides guidance in these human factor considerations. The requirement stated here is intended to be for more complex warning systems and does not include simple warning or caution lights for low oil pressure, over temperature, high or low voltage, and other similar warnings.

The following warnings may be considered for the air vehicle:

a. Stall warning. A warning of pending approach to aircraft stall. Refer to Air Data System and Equipment Specification, AFGS-87211.

b. Gear-up warning. A warning that landing gear has not been lowered while airspeed and altitude are in landing envelope. Refer to Air Data System and Equipment Specification, AFGS-87211.

c. Barometric altitude warning. A system to aid the pilot by presenting him with: command information prior to capture of a preset altitude, deviation notification upon departure from preset altitude, and optional notification just before and at a preset decision height altitude. Refer to Air Data System and Equipment Prime Specification, AFGS-87211.

d. Ground proximity warning system (GPWS). A system to reduce the number of controlled-flight-into-terrain (CFIT) type accidents. The system monitors outputs of aircraft sensors, such as radar and barometric altitude, glideslope deviation and configuration (gear, flaps, etc.); evaluates these aircraft parameter; and gives a warning if a potentially dangerous situation exists. The aircraft parameters are evaluated in pairs with each pair defining a mode (i.e., radar altitude versus radar altitude rate with gear up). A warning area is defined for each of these two dimensional modes. When the aircraft parameters fall within this area, the warning is given (i.e., when an aircraft is descending at 3000 fpm and descends below 1500 feet, the aircraft is in the Mode 1 warning envelope). The basic GPWS system is defined by five modes:

Mode 1 - Excessive rate of descent with respect to terrain

Mode 2 - Excessive closure rate to terrain

Mode 3 - Excessive sink rate after takeoff or missed approach

Mode 4 - Too great of a proximity to terrain for aircraft configuration

Mode 5 - Glideslope deviation.

Improvements are being made in GPWS by a few manufacturers. One improvement is use of an additional parameter of airspeed which is used to modify the warning area of some modes thereby increasing warning time and decreasing the occurrence of nuisance warnings. Another feature of an improved system is an expanded warning vocabulary. A standard GPWS has only a simulated voice warning "PULL-UP" preceded by a "WHOOP-WHOOP" siren. An improved system could have additional voice warnings such as "SINK RATE," "TERRAIN," "DON'T SINK," "TOO LOW," "GEAR," and "FLAP." These warnings have better pilot acceptance because the warning identifies its cause. A standard GPWS is designed for a 2500-foot range radar altimeter and would use only 2500 feet of higher range altimeters in the USAF inventory. An improved system might use the full range of high-range radar altimeter. In the more distant future, one may see the use of weather radar as an input into GPWS for forward-looking capability. Aural warning generation should be centralized if any of the following features are desired:

(1) When warnings must be prioritized.

(2) When a large vocabulary of simulated voice warnings is desired.

(3) When simultaneous warnings are not allowed.

Tone warnings must be distinct and consistent with established practices. Frequency, period, sweep rate, and volume discussions are found in the Stations and Passenger Accommodations Military Standard, MIL-STD-1776.

Human factor testing has shown that voice warning allows for a more immediate pilot response. The vocabulary can be command or informative. Clarity of simulated voice is a function of technique and allotted memory. Vocabulary discussion will be found in the Crew Stations and Passenger Accommodations Military Standard, MIL-STD-1776.

GPWS is required by Federal Aviation Regulations (FAR) for all large turbine-powered aircraft. The requirement compliance date was extended once to 1 September 1976. The extension was due to resolving problems with unwanted or "nuisance" warnings. The solution was to reduce the protection area of the envelopes. In the discussion of the nuisance warning problem, it was evident that one could make the general statement that with larger aircraft, one would notice fewer unwanted warnings. This indicated that one set of envelopes is not ideally suited to all large turbine aircraft in all roles. Flight testing and tailoring the envelope for each aircraft type is recommended. The tailoring must be done by a contractor who has accident data knowledge so that change effects on both warning time and occurrence rate of nuisance warnings can be weighed. One should be cautious if a contractor proposes to provide GPWS capability in some central computer without the aid of a progressive GPWS manufacturer. The governing FAR GPWS TSO is RTCA Document DO-161A, but it does not define all aspects of the warning, such as filtering of signals and delay times. A contractor may take the approach of defining an envelope and then by flight testing keep reducing the protection area until he achieves a satisfactory occurrence rate of nuisance warning with little thought given to the resulting protection against CFIT accidents.

REQUIREMENT LESSONS LEARNED (A.20)

There are numerous, continuing accident reports on wheels-up landings and on controlled-flights-into-terrain. It is believed that many of these accidents could have been avoided if proper warning systems were used.

STANDARDIZATION DOCUMENT IMPROVEMENT PROPOSAL

INSTRUCTIONS

1. The preparing activity must complete blocks 1, 2, 3, and 8. In block 1, both the document number and revision letter should be given.
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I RECOMMEND A CHANGE:	1. DOCUMENT NUMBER MIL-HDBK-87213	2. DOCUMENT DATE (YYMMDD) 961218

3. DOCUMENT TITLE
Electronically/Optically Generated Airborne Displays

4. NATURE OF CHANGE (Identify paragraph number and include proposed rewrite, if possible. Attach extra sheets as needed.)

5. REASON FOR RECOMMENDATION

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a. NAME (Last, First, Middle Initial)	b. ORGANIZATION	
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