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(R) Electrical and Electronic Equipment Cooling in Commercial Transports

RATIONALE

This document is being revised to update references and formatting to the latest style manual and includes other minor changes.

FOREWORD

Commercial transport airplanes have become increasingly dependent on electronics for navigation, guidance, communication, and other airplanes subsystem control functions. The dissipation of heat from these items of electrical and electronic (E/E) equipment is a problem requiring coordinated effort by both the equipment supplier and the airframe manufacturer. The environment in which equipment is installed, the average and local temperatures within the equipment case, and the method of cooling employed have a distinct bearing on the design and reliability of the equipment.

There are two basic methods of cooling the E/E equipment:

a. Passive cooling

b. Active cooling

The passive method relies on free or natural convective cooling to the ambient air surrounding the equipment. The active cooling technique is, in most cases, forced-air convective cooling with the air being either drawn or forced through the equipment case or directed around it. Cold plate cooling using air or some other heat transport fluid is also a suitable design solution for certain active cooling problems.

The current practice is to allocate a small area within the pressurized shell of the airplane for installation of most of the avionic equipment. Being in the pressurized area, the equipment is normally subject to pressures which vary between a maximum (ground) pressure equivalent of -1000 feet (-305 m) and a minimum (flight) equivalent of 8000 feet (2438 m) altitude. Under abnormal flight conditions, such as depressurization on a passenger airplane or during a firefighting procedure on a freighter airplane, continuous operation at pressures equivalent to approximately 15000 feet (4573 m) or 25000 feet (7622 m), respectively, may occur. Considering worst-case transient conditions, such as explosive decompression, exposure may be to pressures approaching the maximum certified altitude of the airplane. This latter condition is, of course, of low probability and short duration such that thermal effects are not usually critical. Considering ground operation, the equipment can be exposed to the maximum certified altitude, which is frequently 14000 feet (4268 m).

For airplanes designed in the 1960s, the predominant cooling system was classified as either “downward draw-through” or “area-cooling” for racked equipment. “Area-cooling” does not force air through the equipment being cooled, but does provide a system to remove heat from the area of the equipment external to the equipment case. For flight deck controls and displays, cooling was generally by the “area-cooling” concept or had no direct cooling at all.

The great increase in digital and compactly packaged equipment and the advent of modern flight deck displays resulted in a corresponding increase in equipment cost and a greater payback resulting from increasing component reliability. This focused attention on cooling and resulted in new ARINC specifications and in more attention to the interface between the airplane cooling system and the E/E equipment. As thermal management has become more important to the continued operation of E/E equipment, more emphasis has been placed on cooling system performance and reliability.

As new E/E equipment is developed, and where reliability sensitivity to temperature can be shown to be reduced, the requirements for cooling that particular equipment may be reduced.

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1. SCOPE

This document considers the cooling of equipment installed in equipment centers, which usually consist of rack-mounted equipment and panel mounted equipment in the flight deck. Instances where these two locations result in different requirements are identified. This document generally refers to the cooled equipment as E/E equipment, denoting that both electrical and electronic equipment is considered, or as an E/E equipment line-replaceable-unit (LRU). The majority of cooled equipment takes the form of LRUs. The primary focus of this document is E/E equipment which uses forced air cooling to keep the equipment within acceptable environmental limits. These limits ensure the equipment operates reliably and within acceptable tolerances. Cooling may be supplied internally or externally to the E/E equipment case. Some E/E equipment is cooled solely by natural convection, conduction, and radiation to the surrounding environment.

This document discusses specification requirements, system design considerations, component design, and system testing. It also discusses the analysis and test considerations for the thermal design of the avionic equipment. The discussion of supplementary cooling systems includes consideration of a refrigeration system.

This document just covers air cooling of equipment. AIR1811 should be consulted for information on liquid cooling of equipment.

Although this document is targeted at transport category airplanes, most of the material applies to other classes of aircraft with possible adaptions.

1.1 Purpose

The purpose of this document is to provide information and guidelines for the analysis, design, installation, and testing of E/E equipment cooling systems on commercial transport airplanes.

2. REFERENCES

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific examption has been obtained.

2.1 Applicable Documents

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

AIR1812 Environmental Constrol Systems Life Cycle Cost

ARP85 Air Conditioning Systems in Subsonic Airplanes

ARP731 General Requirements for Application of Vapor Cycle Refrigeration Systems for Aircraft

ARP987 The Control of Excess Humidity in Avionics Cooling

2.1.2 ARINC IA Publications

Available from SAE ITC, ARINC Industry Activities, 16701 Melford Blvd, Suite 120, Bowie, MD 20715, Tel: +1 240-334-2578, https://www.aviation-ia.com/.

ARINC 404A Air Transport Equipment Cases and Racking

ARINC 408A Air Transport Indicator Cases and Mounting

ARINC 600-20 Air Transport Avionics Equipment Interfaces

ARINC 601 Control/Display Interfaces

ARINC 728 Avionics Refrigeration Cooling System

2.1.3 ASHRAE Publications

Available from ASHRAE Headquarters, 1791 Tullie Circle, NE, Atlanta GA 30329, Tel: 800-527-4723 (U.S. and Canada only) or 404-636-8400, www.ashrae.org.

Standard 52.2 Method of Testing General Ventilation Air-Cleaning Devices for Removal Efficiency by Particle Size

2.1.4 EASA Publications

Available from European Union Aviation Safety Agency, Konrad-Adenauer-Ufer 3, D-50668 Cologne, Germany (for visitors and for mail over 1 kg) and Postfach 10 12 53, D-50452 Cologne, Germany (for mail 1 kg or less); Tel: +49 221 8999 000, www.easa.europa.eu.

AMC 25.1309 System Design and Analysis

CS-25 Certification Specifications for Large Aeroplanes

2.1.5 FAA Publications

Available from Federal Aviation Administration, 800 Independence Avenue, SW, Washington, DC 20591, Tel: 866-835-5322, www.faa.gov.

14 CFR Part 25 Airworthiness Standards: Transport Category Airplanes

AC 25.1309-1A System Design and Analysis

2.1.6 RTCA Publications

Available from RTCA, Inc., 1150 18th Street, NW, Suite 910, Washington, DC 20036, Tel: 202-833-9339, www.rtca.org.

DO-160 Environmental Conditions and Test Procedures for Airborne Equipment

2.2 Related Publications

The following publications are provided for information purposes only and are not a required part of this SAE Technical Report.

2.2.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

AIR1277 Cooling of Military Electronic Equipment

3. REQUIREMENTS

3.1 Government Requirements

Primary Federal Aviation Administration (FAA) and European Aviation Safety Agency (EASA) requirements are given in Title 14 Code of Federal Regulations (CFR)/Certification Standard (CS) 25.1301 and 25.1309. 14 CFR/CS 25.1301 states that the system shall accomplish its intended function. 14 CFR/CS 25.1309 requires that the system shall perform its function under any foreseeable operating condition, within the airplane operating envelope. AC/AMC 25.1309 clarifies the method of applying 14 CFR/CS 25.1309.

Further discussion of civil certification requirements is provided in Section 9.

3.2 ARINC Specifications

3.2.1 Rack Mounted Equipment

Aeronautical Radio Inc. (ARINC) specifications for rack mounted equipment are contained in ARINC 404A and ARINC 600. Included in these specifications is a complete design guide for the equipment manufacturer and for the airframe manufacturer. ARINC 404A is not superseded by ARINC 600, but is supplemented by it. In terms of cooling, a major difference is that ARINC 600 specifies that forced air cooling, where required, should be through the cooled equipment in the upward direction. ARINC 404A specifies a downward flow. The ARINC 600 Phase 1 LRUs should also operate in an ARINC 404A airplane cooling system in order to allow new LRUs to be used on airplanes with ARINC 404A cooling.

There is also a series of ARINC 700 specifications which define avionic systems. These systems then interface with ARINC 600 for cooling and installation. Similarly, there is a series of ARINC 500 LRU specifications that interface with ARINC 404A cooling.

3.2.2 Controls and Displays

ARINC cooling specifications for controls and displays are contained in ARINC 408A and ARINC 601. Included in these specifications is a complete design guide for the equipment manufacturer and for the airframe manufacturer. ARINC 601 provides guidance for the cooling of panel mounted cathode ray tube displays (CRTs), controls and displays, and glareshield mounted equipment.

The ARINC 700 series specifications (discussed in 3.2.1) include controls and displays.

3.3 Other Requirements

Other requirements include airplane imposed design, installed performance, testing, and installation requirements. The ambient temperature and altitude (ground and flight) operating envelopes of the airplane are important items in these requirements. These are determined by a combination of airplane model, airline, and special requirements by the manufacturer of the cooled equipment. In order to ensure a clear relationship between the equipment design and the installed environment, the airframe manufacturer should document testing, environment, performance, and interface/mounting requirements. Installation requirements relate to airplane operating characteristics and procedures and to system reliability and maintainability.

With careful consideration of the installation environment, the manufacturer of the equipment should use all available reliability data to determine what minimum amount of cooling is required.

Cooling system capacity should include an allowance for probable future increases in the amount of equipment requiring cooling.

4. SYSTEM DESIGN CONSIDERATIONS

4.1 Cooling System Performance

Cooling system performance is ultimately defined by the ability to efficiently maintain an acceptable thermal environment for the E/E cooled equipment for both normal conditions and abnormal conditions. Specifically, the performance is measured against the cooling airflow rate requirements at an acceptable temperature. The minimum acceptable cooling performance should be identified.

Of primary importance is the determination of a realistic heat load for the cooled equipment for both ground and flight operating conditions. This is further discussed in 4.7.

In obtaining the required performance it should be an objective to minimize fan power requirements. Since airflow rate is established by the heat load and the appropriate ARINC specification, this can only be accomplished by minimizing fan air pressure requirements. System pressure losses and, therefore, velocities, are critical to sizing the fan. Air velocities of 2000 to 3000 ft/min (10.2 to 15.2 m/s) are considered desirable, especially in the equipment racking. However, when these velocities are exceeded (in long straight ducts, for instance), noise considerations should be observed (see 4.10).

4.2 Cooling System Integration

4.2.1 General

The system for providing cooling to E/E equipment must be integrated with other environmental control systems (such as cabin air conditioning) with regard to cooling air temperature, flow rate, and moisture management.

The maximum allowable cooling air supply or environmental temperatures for E/E equipment are usually higher than those for crew and passenger comfort. Consequently, the serial use of conditioned air, first for human comfort then for equipment cooling, should be considered to minimize the conditioned airflow requirements.

The E/E thermal design engineer should consider the integration of the airplane cooling system with the equipment installation and internal thermal design. This is especially critical for rack mounted equipment where the rack forms a critical element of the airplane cooling system and where numerous items of equipment designed by various manufacturers are required to meet with a specific airplane cooling design concept.

4.2.2 Rack Mounted Equipment

Rack mounted equipment normally consist of LRUs installed on a system of shelves grouped in a centralized location in the airplane. Because of the compact arrangement, which is usually employed, it is common for a rack mounted LRU to have other LRUs above, below, and to the left and right of it.

There are normally interfaces between the cabin air conditioning system and the rack mounted equipment cooling system at both rack air inlet and air exhaust locations. At the air inlet location, the operation of the cabin air conditioning system may significantly affect the temperature of the equipment cooling air. At the air exhaust location, heat being removed from the rack mounted equipment may impact the cabin air conditioning system.

The described interface arrangement would be different for a closed loop cooling system. This is further discussed in 4.3.

The air conditioning system distributes conditioned air to the various airplane zones. There may be little benefit in using air directly from the air conditioning packs for the rack cooling system. This is not recommended. However, it could be considered, provided special attention is given to moisture control.

With the heat produced from E/E equipment, there is the potential of using the discharge air to heat areas such as cargo compartments. In this situation, care should be taken to evaluate heating capability. The heat available will be less than rated equipment heat load. A range of 50 to 70% of rated heat load is considered realistic, unless an overall heat load duty cycle is defined (see 4.7.1). Airplane test experience for similar configurations should be used to define the value to be used.

The airflow rate, inlet temperature to the rack, and allowable pressure drop through the rack and E/E equipment LRUs are key cooling interface parameters which should be coordinated with the rack and LRU designers and ultimately specified in an interface control drawing. Figure 1 is a sketch of the interface of the forced convection cooling air to an avionic rack. The air enters the rack, is ducted between the walls of the rack, and is distributed by a shelf duct which supplies air to each individual LRU. The air exits the LRU through exit holes in the top of the unit and, subsequently, enters the exhaust air return duct.

Several aspects of the rack design impact the airplane cooling system requirements and the overall effectiveness of E/E cooling. The rack pressure loss should be the minimum value consistent with weight, noises, and air distribution considerations. Sufficient pressure drop should be allowed to distribute the air among the various shelves and items of equipment and to effectively collect the spent air exhausting from the units for ARINC 600 designs. Insufficient pressure drop across the exhaust flow control orifices will result in “short circuits” with no air being exhausted from portions of the rack.

The interdependence of E/E equipment pressure drop, air leakage, sealing requirements, and cooling system flow should also be considered. The tolerance structure of the rack required for interchangeability results in a gap between each E/E unit and its mounting tray. To prevent leakage, some installations incorporate a rubber seal in the tray. This seal is subject to wear when the equipment is removed and inserted resulting in maintenance activity. The seal also imposes loads on the connector during insertion and removal. For initial cost, maintenance, and design reasons, it is desirable to eliminate the seal. The amount of leakage between the tray and unit is a function of the pressure drop across the E/E unit. To minimize leakage, it is desirable to keep this pressure drop low, for example 0.2 inch of water (50 Pa). Conversely, it may be advantageous to permit higher unit pressure drop to achieve more effective cooling. Finally, both the high pressure drop across the unit and the high leakage rate have an adverse impact on the airplane cooling system. For each airplane application, the pertinent factors should be considered to achieve an integrated cooling system.

The E/E cooling engineer should review the rack design to assure that thermal and/or fluid “short circuits” are avoided. Of particular importance is the ARINC 600 plenum which may contain both the cooling air and exhaust air separated by a thin barrier with potential failure modes that would direct cooling air into the exhaust plenum. A thermal evaluation is necessary to avoid preheating of the cooling air by the exhaust air.

4.2.3 Controls and Displays

Controls and displays are mainly panel-mounted equipment. Panel-mounted E/E equipment is normally installed so that the front face of the equipment is located on one side of the panel and the main body of the equipment is located on the back of the panel. ARINC 408A is the interface specification covering panel-mounted equipment.

Some integration of the controls-and-displays cooling system and the cabin air conditioning system is possible. Since the controls and displays are in the cockpit, the airflow management of flight deck conditioned air and exhaust air can be integrated with the controls and displays cooling air management. In addition, using part of the cabin air conditioning capacity directly for the control and displays cooling system as a backup can be considered.

Figure 2 illustrates a cooling system for controls and displays located in the flight deck. Cooling air is ducted into the flight deck where it is distributed to the instrument panel and to other items to be cooled. Exhaust air is ducted from the flight deck or enters the lower lobe below the flight deck via holes in the flight deck floor. Alternate means of cooling the flight instruments are to use flight deck exhaust air or in some special cases to use air directly from the cabin air conditioning system.

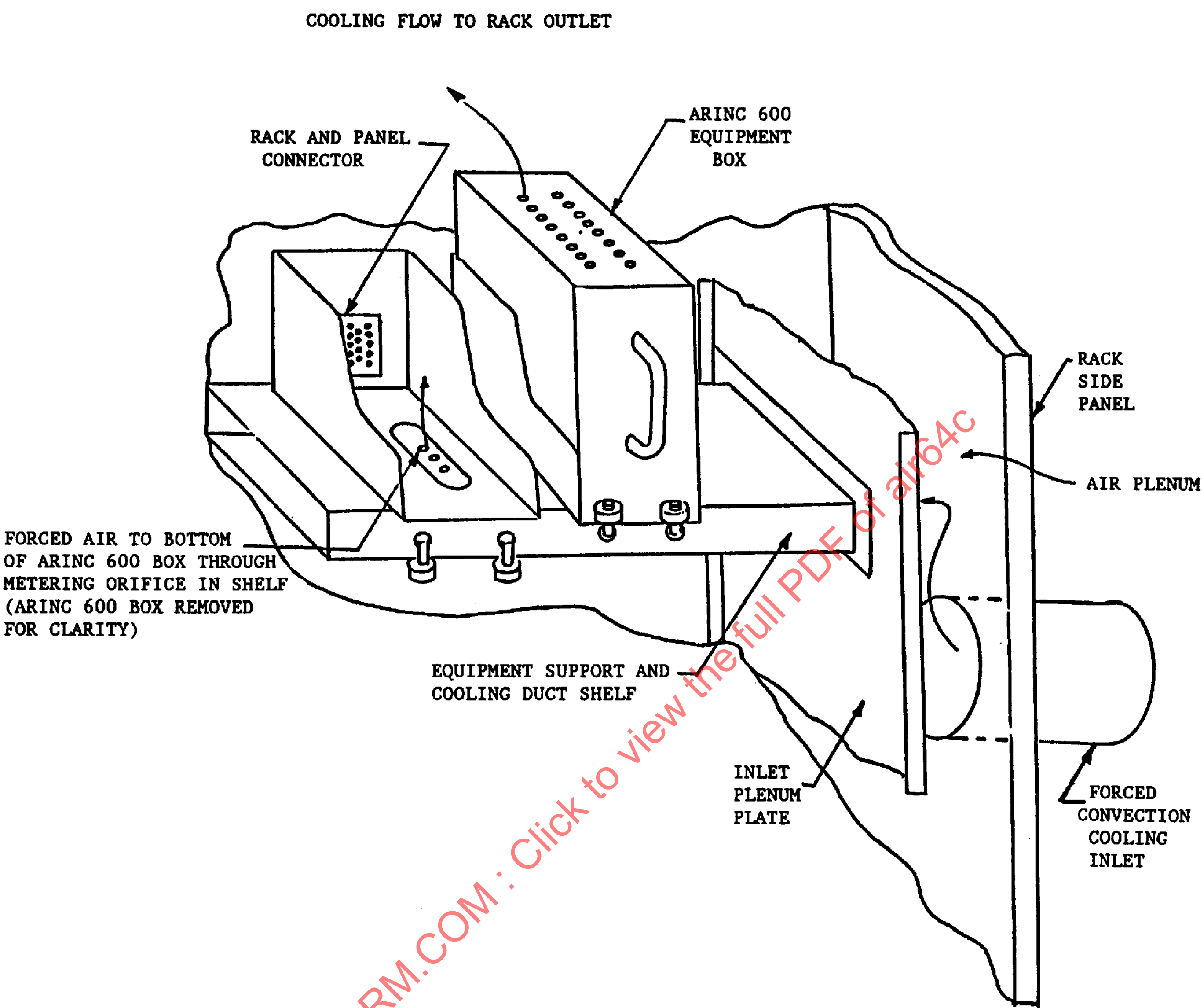

Figure 1 - Interface sketch of a forced convection cooling system

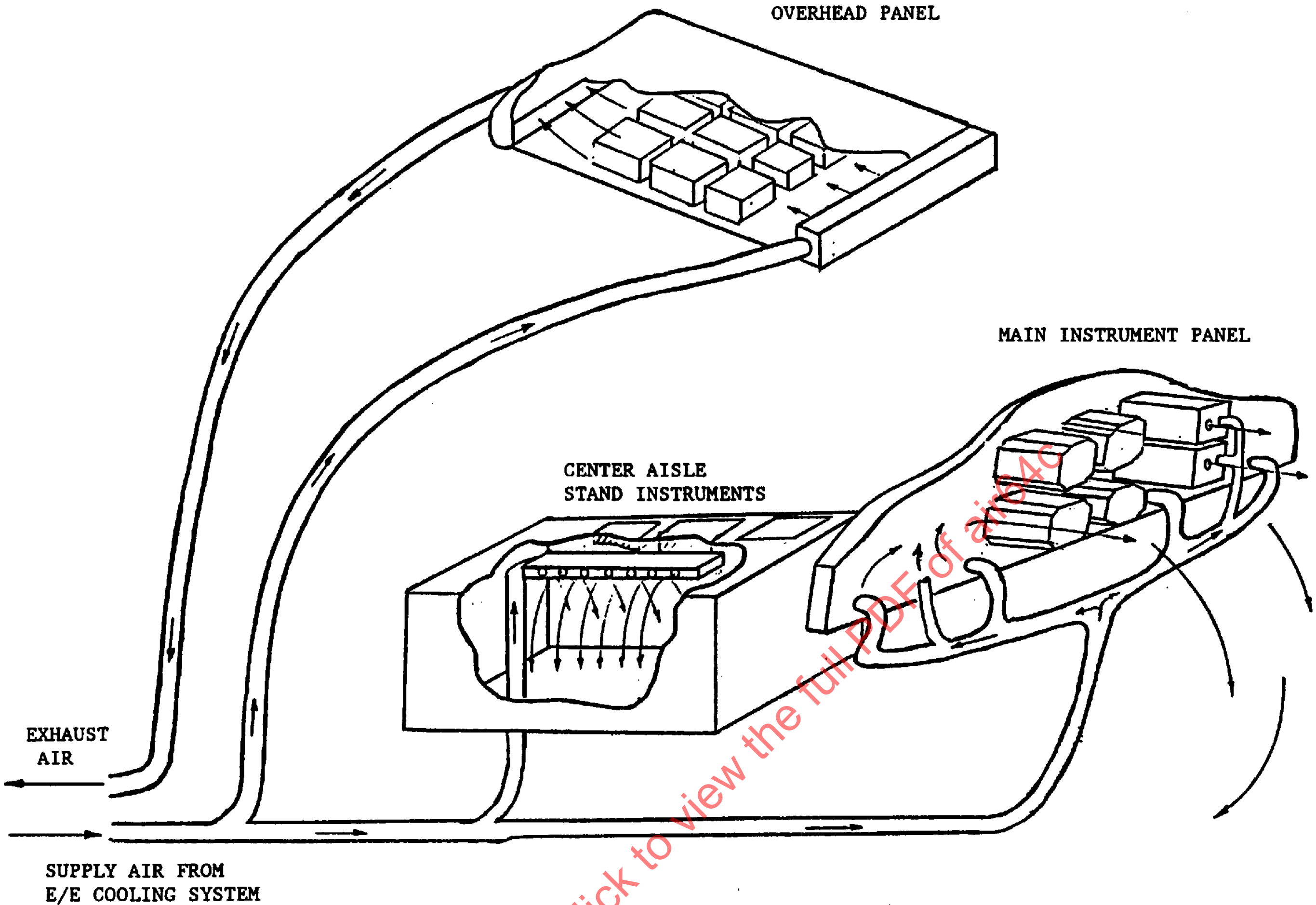

Figure 2 - Typical flight deck cooling system

The use of flat panel displays reduces the major source of heat dissipation in the controls and displays, compared to CRTs. The estimated heat dissipation of some current flat panel displays is about 50 W each compared with 150 W for a comparable CRT. Due to the low heat loads typical of flat panel displays, a passive thermal control system relying on natural convection cooling with no forced air cooling may be adequate. Display-generating electronics, if they are part of the flat panel display, will increase the heat load at the display location.

4.3 Closed Loop Design Concepts

The increased use of cabin air recirculation in order to reduce engine bleed airflow rates and thereby reduce fuel consumption, has reduced the amount of air available for use as an avionic heat sink. When avionic heat is managed within the airplane, the use of closed loop cooling systems for the avionics becomes attractive. The use of the closed loop will minimize undesirable effects of heat and smoke on the conditioning systems for the passenger and crew compartments. Closed loop designs are also advantageous from the standpoint of minimizing E/E equipment contamination.

Heat sinks or cooling techniques which can be used with closed loop systems include skin heat exchangers and supplementary cooling systems (see Section 8).

Figure 3 shows an example of a closed loop avionic cooling system. The system provides upward-flow cooling to the rack-installed LRUs and to the flight deck equipment. A vapor cycle refrigeration unit could be used on the ground (as shown) or the “loop” could be opened, by the means of valves, in order to circulate airplane on-board air, or outside ambient air, through the equipment racks. During flight the system circulates the cooling air through the avionics and through the skin heat exchanger where the air is cooled before returning to the avionics. Only one of the two supply fans is normally operated. The second fan provides redundancy if the operating fan fails.

Cool air is supplied to the avionics rack and flight deck. The return air is then cooled by either the vapor cycle refrigeration unit or the skin heat exchanger and the air is recirculated in a closed loop mode.

It may be difficult to produce a totally closed loop design. When, for example, the design is not "closed loop" at the exhaust from the cooled equipment, it is acceptable for the system to exhaust air from the vicinity of the equipment, as well as to exhaust air which has passed through the equipment. A combination of closed loop and open loop systems may be considered. For instance, the closed loop system of Figure 3 could be used inflight with skin heat exchanger cooling and valves could be added to use ambient air cooling (in an open loop) on the ground.

4.4 Ground Cooling Considerations

4.4.1 Operating Conditions

As mentioned in 3.3, airplane ambient temperature and altitude operating envelopes are important requirements. Of those requirements, ground operation in hot weather conditions will often dictate the cooling system design. It should be noted, however, that in unpressurized aircraft; critical electronic cooling considerations can occur during operation at high altitude and should always be checked.

All E/E equipment may need to be powered whenever an electrical external power source is connected to the airplane, with or without cabin air conditioning. During maintenance operations avionics may be powered with no cabin air conditioning being provided. Therefore, operation with and without cabin air conditioning, as it relates to E/E cooling, should be considered.

A significant consideration during ground-cooling operation is the initial power application to E/E equipment after the airplane has soaked in a high temperature environment.

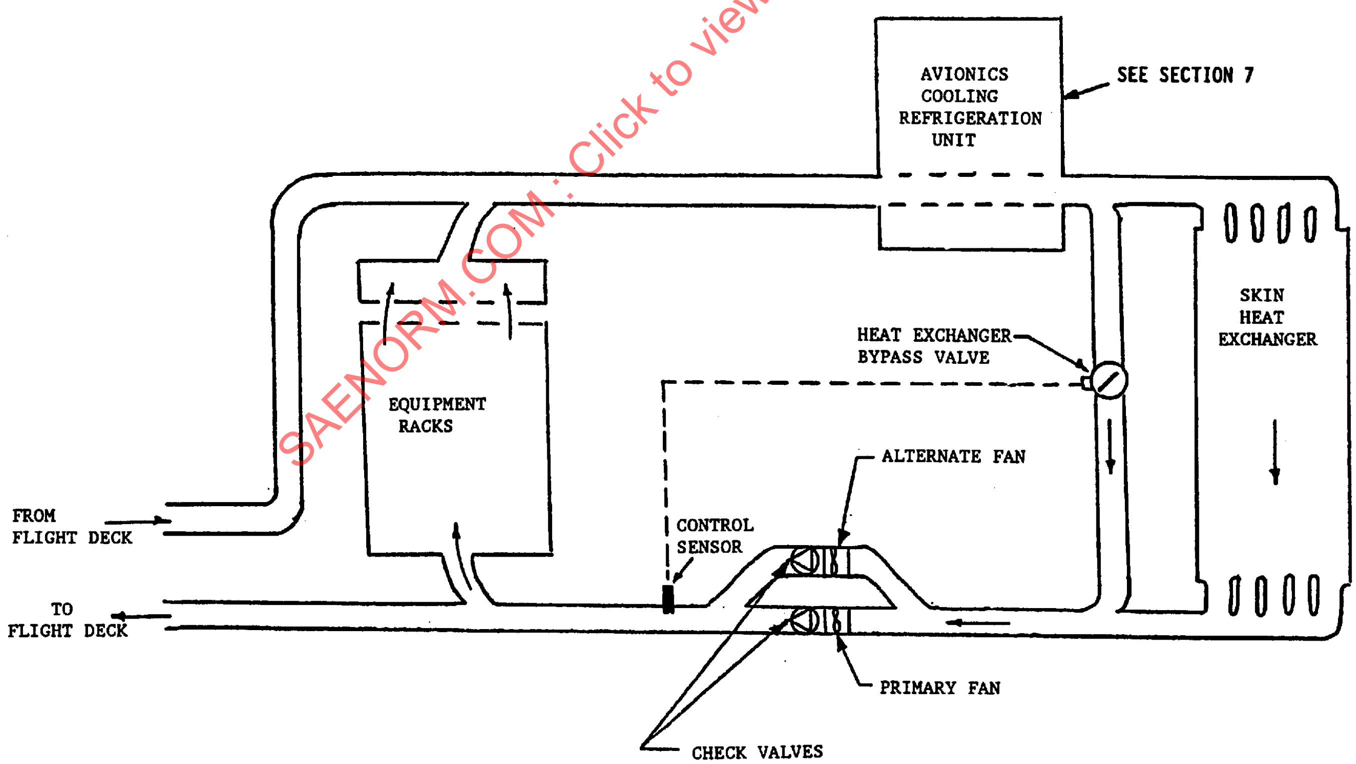

Figure 3 - Closed loop cooling system

The cooling system configuration and E/E equipment thermal design should provide an acceptable thermal environment without the use of airplane or ground supplied refrigeration (but with the E/E cooling system operating) in hot weather conditions. This has special importance relative to maintenance operations. When short duration maintenance operations are concerned, this objective should be considered a requirement.

4.4.2 Equipment Cooling System

The configuration of the cooling system should consider the cooling available from the use of external ambient air (from outside the airplane) and the use of air from inside the airplane.

The cooling system should be capable of handling the transient conditions associated with electrical power application to the airplane, in hot weather conditions, without exceeding any temperature limits. These limits can be associated with preserving E/E equipment reliability as well as with cooling system control limits.

Generally, the cooling systems described in 4.1 and 4.2 will perform satisfactorily on the ground. However, as equipment thermal environments on the ground are usually more severe than those observed in flight, the system performance on the ground should be evaluated with regard to the ARINC specifications discussed in 3.2.

4.4.3 Use of External Ambient Air

When an airplane is exposed to hot weather conditions, without being air conditioned, the air temperatures inside the aircraft may be higher than the external ambient air temperature. In this type of situation, cooling available from external ambient air may be considered.

4.4.4 Use of Airplane Internal Air

Airplane internal ambient air temperatures can be very high if an airplane remains in an unconditioned state during hot weather conditions. These temperatures can be greatly reduced in most airplane compartments by operating the cabin air conditioning systems and may also vary from one compartment to another. These temperature variations should be considered in defining a cooling system configuration as they may affect both the environment of the E/E equipment and the temperature of the cooling air.

Normally, commercial airplanes allow for connection of the main cabin air conditioning distribution system to a refrigeration ground cart for cabin air conditioning. A ground air source can be used for operation of the airplane on-board air conditioning systems. Where necessary, there is usually the possibility of using cabin air conditioning to reduce the temperature environment of the E/E equipment.

For controls and displays on the flight deck where the “greenhouse effect” can result in very high temperatures in hot weather conditions, the use of cabin air conditioning can be especially beneficial.

4.5 System Controls and Indication

Controls should be provided to allow both automatic and manual operation of the system. System operating status and indications of malfunctions such as cooling failure, smoke, and overheat should be displayed to the crew when crew action or awareness is required. This includes status information so that airplane dispatch capability can be determined. When redundant fans and valves are provided, automatic shutdown of the failed unit plus startup of the backup units should be initiated without crew action. Information on failures should automatically be recorded so that the failed unit can be quickly located and replaced by the maintenance crew.

4.6 System Penalty Analysis

System penalty analysis should include the evaluation of life cycle costs.

Cooling is required in order to maintain all the rack-mounted equipment and controls and displays within their specified operating limits. In addition, cooling is usually justifiable because of increased component life and, therefore, lower life cycle costs (refer to AIR1812). Any increase in cooling system capacity beyond the minimum necessary should be justified by showing that the cost saving due to reduced E/E equipment life cycle costs more than offsets the increased cooling system costs associated with the larger capacity system. These include any increase in cooling system maintenance cost, increase in initial hardware and development cost, and the cost of additional fuel burned due to any increased weight and energy consumption of the larger capacity system.

System penalty analysis promotes the concept of smaller (higher velocity) ducting; however, this must be traded against increased fan power requirements and system noise.

When increased cooling system capacity is provided by increased system complexity, a significant penalty may be the increased maintenance costs due to reduced reliability.

4.7 Thermal Design

4.7.1 General

The thermal design of the E/E cooling system seeks to maintain electronic equipment temperature within acceptable limits. This is carried out by managing cooling air temperature, airflow rate, compartment temperature, and E/E equipment arrangement. This design activity usually takes place after E/E equipment specifications have defined what cooling is to be supplied to each LRU but before detailed thermal analysis of the LRU itself has occurred (see Section 6).

There are several possible sources of cooling air including cabin exhaust air, conditioned cabin supply air, and cooling air from a dedicated cooling unit. Ambient air temperatures in an equipment center can be as much as 20 to 30 °F (11 to 17 °C) higher than the cabin exhaust air temperature during hot-ground conditions. Therefore, with hot-day-ground conditions there is a distinct advantage in coupling the rack cooling air temperature closely to cabin exhaust temperature.

If high pressure supply air fans are used to provide cooling, the temperature rise due to the fan should be determined and taken into account if it is significant in comparison to the E/E heat rejection rate. It is important to have accurate heat load design values for the E/E equipment, especially for the equipment which is supplied with cooling air, in order to properly size the cooling system and to configure the distribution system. The duty cycle for the cooled equipment should be known and considered in the design of the cooling system. If the maximum heat dissipation is used without a duty cycle, the cooling system will be oversized.

The recommended airplane design ambient temperatures are those defined in the ambient conditions section of ARP85. The equipment cooling air and ambient design temperatures should be those defined in the appropriate ARINC specification for normal and abnormal operating conditions. The ARINC documents provide the corresponding cooling airflow rates at the design conditions.

Thermal management of the E/E equipment bay should consider the effects of high or low skin temperature on the E/E equipment environment and cooling air temperatures. Heat infiltration into the E/E equipment bay should also be factored into the thermal management process. This is important as thermal insulation on the airplane skin in these locations may be minimized for weight saving.

4.7.2 Heat Load Allocation

In the analysis of avionic rack cooling requirements, the division of the equipment heat loads between that transferred to the rack cooling airflow and the remaining heat load rejected to the compartment should be considered. Approximate divisions for the principal types of equipment installations are shown in Table 1.

The heat rejection characteristic depends upon the type of rack installation. An enclosed rack would be one where the rack is enclosed in a cabinet, with cooling air directed into and out of the cabinet. Installation type “open rack-draw through” refers to the installation where local ambient air is drawn through the racked equipment, which is the normal implementation of ARINC 404A. Installation type “open racks-blow through” refers to the installation where cooling air is ducted into the racked equipment and where the exhaust air is ducted away from the local ambient; this being a method of implementing ARINC 600 on some commercial transport airplanes.

The following allocation assumes that there is an exhaust system in each case and that the exhaust system is installed just above the equipment for the blow-through concept, with the exhaust and supply airflow rates essentially the same. Even with this airflow equivalency there is an airflow exchange with the compartment and this is reflected in the heat load allocation. This allocation would also be appropriate for flight deck or cabin mounted equipment if the supply and exhaust airflow configurations were similar.

Table 1 - Heat load allocation guide

Type of Installation	To the Compartment Spillage of Cooling Air (Percent)	To the Compartment Heat Loss Directly from Equipment (1) (Percent)	To Cooling Air (Percent)
Enclosed Racks	0	0	100
Open Racks-Draw Through	0	15	85
Open Racks-Blow Through	25	15	60 (2)

(1) Conduction, radiation, and convection from outside surfaces of equipment case.
(2) The division between these values is dependent upon how much of the cooling air is collected by the exhaust system and how much spills into the compartment.

4.7.3 Cooling Classification for Equipment

The class of cooling for the E/E LRU is an important parameter in the thermal design. The four classes of cooling are:

a. Forced-air-cooled

b. Case-cooled

c. Perforated or no-case

d. Miscellaneous

The type of cooling is usually specified in the specification issued by the airframe manufacturer to the E/E equipment designers.

4.7.3.1 Forced-Air Cooled Equipment

This class applies to all actively cooled equipment for which the primary cooling mode is forced-air applied directly to the interior of the equipment. Air movement through the equipment may be produced by the application of draw-through or blow-through cooling supplied by the airplane environmental control system. This equipment class is commonly installed in equipment racks and also may apply to flight deck panel mounted displays. The design goals for this class of equipment include optimization of coolant paths and expenditure of available pressure drop in a way that will maximize cooling of temperature sensitive parts. The use of internal fans is not usually allowed.

4.7.3.2 Case-Cooled Equipment

This class applies to all passively cooled equipment cooled primarily by heat transfer from the external case (by convection, conduction, and radiation). This class applies to panel or rack-mounted equipment and also to individually mounted equipment not conforming to ARINC standard case sizes but having an enclosed case. The internal cooling design for the class of equipment should be predicated on transfer of the internally generated heat to the case of the equipment at the case temperature specified while minimizing the component operating temperature.

4.7.3.3 Perforated or No-Case Equipment

This class is a special case of passive-cooling and applies to all panel, rack, or individually mounted equipment without a cover or with screen-type or perforated cases. The primary cooling mode for this class of equipment is by natural convection. For panel installations, natural convection currents may be suppressed and the ambient air temperature may be stratified because of the presence of adjacent equipment. This stratification should be avoided if at all possible. A printed circuit card designed for a card file is considered to be in this class.

4.7.3.4 Miscellaneous Equipment

This class applies to E/E equipment primarily cooled by convection where temperature qualification in an ambient environment is satisfactory. This class is intended to include such electromechanical equipment as switches, relays, motors, servo valves, actuators, and other miscellaneous equipment.

4.8 Particulate Contamination

If particulate contamination in the cooling air is not controlled, it can degrade the performance of the E/E cooling system.

A low-cost, throw-away filter that is readily accessible or a centrifugal separator type air cleaner are common methods of controlling contamination (5.5). As a filter builds up contamination, the device will become more effective in separating smaller sized particles. However, pressure drop across the filter will increase correspondingly, thereby reducing overall cooling airflow. The cooling air fan should have sufficient capacity to maintain flow with this increased pressure drop. The major purpose of air filters or cleaners is to maintain the as-designed thermal characteristics of component heat transfer and therefore to maintain the required E/E equipment reliability. There may also be a performance benefit to fans and sensors. Failure of the system filter or cleaner to remove contaminants which would otherwise block critical internal airflow or heat paths within the cooled equipment will result in equipment failure.

An indicator showing when a filter is clogged, or a regular filter maintenance interval, is normally required.

The requirement for particulate contamination removal can be more easily met with a closed-loop cooling system (4.3).

4.9 Moisture

Moisture considerations are important where avionics are directly cooled by air. Normally, airplane E/E equipment has to pass qualification testing including the effects of humidity. However, the cooling system should be designed to prevent the presence of free water. When considering any interface with the cabin air conditioning system, the generation of free water within the air conditioning system should be considered. Closed loop systems (4.3) have an advantage in minimizing moisture buildup.

The cooled equipment should be protected from moisture generated or collected in airplane compartments located overhead and from rain, etc., in the airplane external environment, whether or not this moisture is transported by the cooling system.

The presence of free moisture in the avionics may cause corrosion within the LRUs and electrical connectors. Avoidance of water generation, water traps, and some reheating of the air, or selection of a warmer air source, should be considered in order to minimize the possibility of entrained moisture entering the avionic LRUs.

4.10 Noise

Cooling system noise may impact the passenger cabin and/or the flight deck noise environment. At a high level, this will interfere with the ability of the crew to communicate. At lower levels, it may be distracting. In particular, it can be a problem during ground operations, when it is probably the only noise present in the flight deck. To minimize impact, the noise should have a broadband character; whistles or pure tones should not be present.

Most of the flight deck equipment cooling noise is generated inside or around the instruments when turbulent air impinges on the various components. The noise penetrates into the flight deck through gaps in and around the instrument panels or, after being structurally borne through the components, by radiation of the panel into the flight deck.

The most effective way to control cooling airflow noise is to limit air velocities to 3000 ft/min (15.2 m/s) in the system since noise generation due to turbulence inside ducts is proportional to the sixth power of the air velocity. Air velocity may be acceptable at 4000 ft/min (20.3 m/s) in areas remote from occupants. With reference to flight deck noise, orifices to control airflow should be installed in the system as far away as possible. The pressure drop across any orifice communicating directly with the compartment should be less than 0.5 inch of water (124 Pa). Orifice design should also be selected for low noise generation. Locally in flight deck areas, a velocity of 2000 ft/min (10.2 m/s) is more appropriate according to ARP85. Note that 4.1 also discusses duct velocities.

Fans should be properly isolated from the structure to prevent fan noise being transmitted through the structure and penetrating into the passenger cabin and flight deck. Also, isolation between fans and ducting is important since the lightweight ducts used in aircraft are very effective noise radiators. Case radiated noise should be controlled by fan specification.

Consideration should be given to noise relative to ground maintenance operations, especially from the standpoint of fan noise and overboard exhausts.

4.11 Failure Modes

The design of the system should be investigated by failure analysis methods including “fault trees.” Any cooled equipment which is critical from a safety standpoint should have a cooling backup system provided. This backup can be initiated automatically or manually by the flight crew.

An analysis should be carried out to determine the effect of a failure, criticality, indication, and recommended crew response. Analysis which shows not only the failure mode but possible cause of the failure can also be beneficial.

Each component to be cooled should be analyzed to determine how critical it is to airplane safety and how susceptible it is to failure if cooling fails.

4.12 Reliability and Maintainability

System reliability has an impact on airline economics and can also impact airplane safety. The considerations of 4.11 may be the basis for determining cooling system reliability requirements. Maintainability of components such as fans, filters, valves, etc., should be simplified by easy access for either an empty or a fully loaded airplane.

5. COMPONENT DESIGN CONSIDERATIONS

5.1 Fans

In addition to complying with the normal operating performance and with certification requirements, the fan design should consider the following:

a. Ability to provide acceptable performance under conditions of system degradation and fan contamination prior to failure indications

b. Ability to operate without damage in the stall or surge conditions

c. Thermal protection for motors (including locked rotors)

d. For three-phase motor-driven fans: the ability to lose one phase without damage to the motor

e. Impact on cabin and ground (maintenance) noise, including structurally borne or case radiated noise

f. Safety provisions such as inlet or exhaust screens

g. Stall margins should provide for system degradation (filter contamination, etc.) during normal in-service operation

The fan performance should allow for any predicted growth in cooling requirements and for E/E equipment options required by different airlines. Axial fans can provide high performance at relatively low weight; however, the stall characteristics are better with mixed flow or centrifugal fans.

5.2 Heat Exchangers

Heat exchangers are used for closed-loop systems as discussed in 4.3. Except for use with supplementary cooling systems (see Section 8), heat exchangers are not normally used for ground maintenance conditions. If applied to flight conditions, heat exchangers can provide adequate cooling for a significant part of the airplane operating envelope. Since the cooling system is an airflow and heat management system, heat exchanger leakage should be kept at a minimum, especially for ducts supplying cooling air from the fan to the E/E equipment. The use of a heat exchanger, because of the widely varying temperature of available heat sinks, may require the use of a temperature control system.

Since cooling system pressures are normally quite low, heat exchangers often can be designed for low weight.

5.3 Ducting

Duct detail design is determined by pressure drop, weight, and handling (or other maintenance) criteria. Pressure drop may be critical for fan sizing and could limit duct velocities (4.1). Noise may also determine duct size (4.10). Abrupt line size changes, sharp bends, mitered corners, flow obstructions, and interior wall roughness should be avoided to reduce pressure drop and minimize noise. Duct interior walls should be smooth to minimize pressure loss and care should be taken to ensure that the material is not moisture absorbent. With the normal low pressure used in the cooling system, duct wall strength requirements are determined by collapsing loads, including handling and “foot-traffic” in maintenance areas of the airplane.

5.4 Duct Connectors

Duct connectors should be of a standard and readily available design and size. Since this is a low pressure system, connectors do not carry large loads so they can be very light. Elastomer boots and band clamps are commonly used.

Where required for system reliability, duct connectors (and supports) should be designed such that ducting integrity is preserved when one connector (or support) is failed.

5.5 Filters and Air Cleaners

Filters and air cleaners can be of the particulate type arranged to control quality of the entire cooling air supply, or could be smaller devices controlling smaller sections of the system. Some avionic equipment may have individual filters at the LRU level.

Care should be taken to not specify a filter of too fine a collection characteristic (4.8). In general, as is required by ARINC 600, a 400 µm filter is adequate for E/E cooling systems. Maintainability (4.12) is also a major criterion and may determine size due to space constraints. A maintenance filter change period of 2000 to 3000 operating hours should be a target. Filters should be capable of being easily replaced, including during airplane in-service conditions. New filters should have a low pressure drop at rated flow; for example, 0.2 to 0.4 inch of water (50 to 100 Pa).

Air cleaners may be of the centrifuging type requiring a purge airflow to carry away the particulate contamination. When designing the air cleaner purge system the type of contamination and the location of its discharge should be considered. Air cleaners may be subject to performance degradation with no clear indication that this is occurring.

The filters and air cleaners should be capable of high removal efficiency (90 to 95% by weight) for lint and other low-density contaminants. In some designs, high efficiency for higher density dust or sand particles may be appropriate.

The weight arrestance test described in ASHRAE Standard 52.2 can be used as a basis for contamination testing, with appropriate modification of the contamination mix.

5.6 Water Removal Provisions

Water separators should be considered wherever free water can enter the system or be produced by condensation in the system. These devices, where necessary, should be simple and lightweight. Due to potential problems with mixtures of water and dirt, water drains should be designed to minimize clogging. A design capable of dealing with water running along duct walls should suffice, such as a scupper with a positive purging drain. Refer to ARP987 for more information regarding control of water in cooling systems.

5.7 Sensors/Detectors

Design of sensors and detectors should take into account fault verification methods and in-service degradation due to contamination and moisture.

The system requires a method of detecting inadequate performance. Temperature and/or flow or cooling effect detectors can be utilized. The use of flow and cooling effect detectors requires tailoring of the detector to the installed location in order to adequately measure performance characteristics. The detection system should be directly related to the results of 4.11.

5.8 Vapor Cycle Systems

Since most electrical and electronic equipment do not require pressurization, vapor cycle systems are a consideration for cooling this equipment. Refer to ARP731 for guidance in the use of vapor cycle systems.

6. THERMAL DESIGN OF COOLED EQUIPMENT

6.1 General

The purpose of thermal design is to obtain the required E/E equipment reliability with a minimum cost and weight and without putting any unnecessary reliance on the cooling system. It should be a major objective to use state-of-the-art thermal design concepts and component reliability data to minimize cooing requirements.

The internal thermal design of E/E equipment is an important factor in efficient cooling. The junction temperatures of the electronic components are ultimately the indication of the success of the thermal design. Often the cooling air temperature is fixed so that the greatest reduction in electronic component junction temperature may be accomplished through efficient thermal design of the equipment.

The design should be approached with the attitude that the thermal analysis must be of sufficient quality and depth to ensure acceptable junction temperatures.

As discussed in 6.3, testing should be carried out on both prototype and production components. However, temperature data from prototype components may not be totally representative (critical when temperatures are marginally acceptable) and the testing of production components may occur too late to readily incorporate any necessary design changes. Due to the high costs of modifications, these problems, which are identified late in a program, tend to be accepted without change or improvement and become a source of high failure rates in service.

An overall program of analysis and test is necessary during the design and qualification of the equipment if a successful thermal design is to be accomplished.

6.2 Thermal Analysis

Thermal analyses of the avionic system should be conducted in parallel with the electrical design and packaging. As the initial packaging concept is developed, the thermal design concept must also be formulated. Using power dissipation estimates, the packaging must be designed to assure that high power dissipation parts are not concentrated or located where inefficient thermal paths will not allow efficient transfer of the heat to the cooling medium. The overall packaging and power dissipation will allow the thermal designer to determine if the unit should be passively or actively cooled. As the packaging concept develops and the circuit design is defined, the thermal design engineer can initiate a preliminary thermal analysis. The circuit designer at this time should provide preliminary heat dissipation values and identify the electrical devices finally selected. The temperature limits for each electronic part are then determined. Both the maximum temperature limit for the severe environment and a “derated” temperature limit are used to assure that the avionic unit will provide the required reliability for long-term operation. An early preliminary analysis is important for identifying part changes (higher temperature electronic parts and/or reduced part power dissipation and/or higher power capability parts) and potential packaging changes to improve the internal heat transfer.

As the electrical design is refined, the thermal analysis should also be updated. The analysis techniques also become more refined. The preliminary analysis may require only hand calculation. As the design progresses, computer-aided design (CAD) techniques will become necessary to analyze the complex heat transfer paths. Computer programs are available to assist in the design of printed circuit boards to optimize both electrical and thermal component locations on the board.

The electrical designer may utilize a breadboard unit to verify the electrical design. These breadboard units may also be used to assist the thermal designer in checking the previously predicted heat dissipations in the electrical components, which may have been conservative. The thermal engineer should identify the parts of the circuit in which the power dissipation should be measured. The breadboard tests generally do not provide representative temperatures because the final packaging is not duplicated.