

AEROSPACE INFORMATION REPORT

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(R) Heat Sinks for Airborne Vehicles

RATIONALE

Aerospace heat loads temperatures, magnitudes and time durations have changed significantly due to more electric aircraft architectures and new heat loads. Similarly, the vehicle capability penalties and evaluation methods for the heat sinks have changed due to continued pressure for fuel burn reduction along with noise and observability reduction.

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1. SCOPE

This document summarizes types of heat sinks and considerations in relation to the general requirements of aircraft heat sources, and it provides information to achieve efficient utilization and management of these heat sinks. In this document, a heat sink is defined as a body or substance used for removal of the heat generated by thermodynamic processes. This document provides general data about airborne heat sources, heat sinks, and modes of heat transfer. The document also discusses approaches to control the use of heat sinks and techniques for analysis and verification of heat sink management. The heat sinks are for aircraft operating at subsonic and supersonic speeds.

2. REFERENCES

2.1 Applicable Documents

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 exemption has been obtained.

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.

AIR64	Electrical and Electronic Equipment Cooling in Commercial Transports
ARP217	Testing of Airplane Installed Environmental Control Systems (ECS)
ARP780	Environmental Systems Schematic Symbols
AIR1168/3	Aerothermodynamic Systems Engineering and Design
AIR1168/8	Aircraft Fuel Weight Penalty Due to Air Conditioning
AIR1277	Cooling of Military Avionic Equipment
AIR1811	Liquid Cooling Systems
AIR1812	Environmental Control Systems Life Cycle Cost

2.1.2 ARINC Publications

Available from ARINC, 2551 Riva Road, Annapolis, MD 21401-7435, Tel: 410-266-4000, www.arinc.com.

ARINC 404A	Air Transport Equipment Cases and Racking
ARINC 600	Air Transport Avionics Equipment Interfaces
ARINC 628P7	Cabin Equipment Interfaces Part 7 Cabin Equipment Cooling, General Specification

2.1.3 FAA Publications

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

FAA Advisory Circular AC23-1309-1 (EASA respective document - Copy Rick Gains EASA reference style): "Systems Safety Analysis and Assessment for Part 23 Airplanes"

FAA Advisory Circular AC25-1309-1: "System Design and Analysis"

FAA Advisory Circular 29-2C: "Certification of Transport Category Rotorcraft"

2.1.4 Code of Federal Regulations (CFR)

Available from the United States Government Printing Office, 732 North Capitol Street, NW, Washington, DC 20401, Tel: 202-512-1800, www.gpo.gov.

U.S. Code of Federal Regulations, Title 14, Federal Aviation Regulation, Part 23 - "Airworthiness Standards: Normal, Utility, Acrobatic and Commuter Category Airplanes"

U.S. Code of Federal Regulations, Title 14, Federal Aviation Regulation, Part 25 - "Airworthiness Standards: Transport Category Airplanes"

U.S. Code of Federal Regulations, Title 14, Federal Aviation Regulation, Part 27 - "Airworthiness Standards: Normal Category Rotorcraft"

U.S. Code of Federal Regulations, Title 14, Federal Aviation Regulation, Part 29 - "Airworthiness Standards: Transport Category Rotorcraft"

2.1.5 Applicable References

Coons, L.L., (1986), "Propulsion Challenges for Hypersonic Flight," AIAA Paper No. 86-2620, October, 1986.

Fluegel, K., (1997), US Patent No. 5,702,073, Modular Liquid Skin Heat Exchanger.

Franklin, J. and Leonard, C., "Thermal Characteristics of Standardized Air Force Avionic Enclosures," SAE Technical Paper 831103, 1983, doi:10.4271/831103.

Howard, R.W., (1989), US Patent No. 4,819,720, Skin Heat Exchanger.

Humphries, W.R., (1974), Performance of Finned Thermal Capacitors, NASA Technical Note TN D-7690, July, 1974.

Humphries, W.R. and Griggs, E.I., (1977), A Design Handbook for Phase Change Thermal Control and Energy Storage Devices, NASA Technical Paper No. 1074, November, 1977.

Kays, W. and London, A.L., (1984), Compact Heat Exchangers, 3rd Edition, McGraw-Hill, New York, 1984.

LeClaire, R., (1975), "Evaluation of the Overall Fuel Mass Penalty of an Aircraft System", Aeronautical Journal, May, 1975.

Letton, G.C., Jr., (1979), "Air Versus Liquid Cooled Avionics," Air Force Planning Conference - Avionics: Survivability, June, 1979.

Magnus, A.E., et al., (1981), A Computer Program for Predicting Subsonic or Supersonic Linear Potential Flows About Arbitrary Configurations Using a Higher Order Panel Method, NASA CR-3251, -3252, -3253, -3254, 1981.

Schultz, H.D., (1965), Thermal Analyzer Computer Program for Solution of General Heat Transfer Problems, NASA CR-65581, 1965.

Sheffield, J.W. and Wen, C., (1989), Phase Change Materials for Spacecraft Thermal Management, AFFDL-TR-88-2133, WPAFB, Dayton, Ohio, February, 1989.

Smith, J.R., (1983), SINDA - Systems Improved Numerical Differencing Analyzer User's Manual,

TRW Report 14690-H001-BC-00, Revision 3, March, 1983.

Swain, E.F. and Letton, G.C., Jr., (1979), "Thermal Control for Pod Mounted Avionics," ASME Paper No. ENAs-2, July, 1979.

Wiese, D., "Thermal Management of Hypersonic Aircraft Using Noncryogenic Fuels," SAE Technical Paper 911443, 1991, doi:10.4271/911443.

Woodward, F.A., (1980), USSAERO Computer Program Development, Versions B and C, NASA CR-3227, April, 1980.

3. THERMAL MANAGEMENT CONSIDERATIONS

Heat sink thermal management requires the consideration of several factors to achieve the desired temperature and heat rejection rate, without jeopardizing aircraft design goals such as:

- life-cycle cost;
- performance;
- weight;
- reliability;
- maintainability;
- operating envelope;
- safety.

Achievement of these goals requires an appropriate match of the heat sink and the maximum allowable heat source temperatures. As the absolute value of these temperatures approach each other, the driving force available to reject heat decreases exponentially, leading to significant integration challenges.

The use of heat sinks influences the design and performance of aircraft. Typically these influences are considered and integrated with the aircraft's major systems during the design process. These effects are most often associated with aerodynamic drag, propulsion system performance, weight, and size of the aircraft and are minimized through the application of thermal management integration techniques.

Many factors must be considered when selecting a heat sink:

- heat sink thermal properties, transport capability, environmental and safety aspects;
- temperature level;
- thermal control requirements.

Additionally, for heat sources, the following factors must be considered:

- duty cycle;
- rate of required heat rejection;
- temperature level;
- heat transport method;
- thermal control requirements.

4. HEAT SOURCE CHARACTERISTICS

The major heat sources are waste heat from systems installed on the aircraft, metabolic heat from crew and passengers, heat from the engines, heat transferred through the airframe from the ambient environment, solar heat load and heat generated by air friction and stagnation effects on the airframe. Much of the heat generating equipment in aircraft requires cooling and, therefore, heat sink management to maintain proper operating temperatures. The quantity, rate and temperature of the heat to be rejected to a heat sink are determined by the heat source and by the capacity and effectiveness of the heat sink system. Some heat rejection rates vary as operating conditions of the aircraft change.

Brief discussions of heat sources are presented in this section and each heat source is classified as occupied or unoccupied. These heat sources include personnel; electronic (avionic) equipment; engine bleed air; vapor cycle refrigerant; mechanical power systems such as hydraulics, pumps, engine lubrication; electrical power systems such as generators, motors, inverters; unoccupied zones with temperature sensitive equipment and fuel. Typical design temperature considerations for initial heat sink matching to heat sources are found in Table 1, and are discussed in the following sections.

4.1 Cabin or Cockpit (Occupied Areas)

Personnel occupied volumes (cockpit and cabin) require temperatures near 70 °F (21 °C), with some variation in temperature permitted and even desired. Personnel heat sources are metabolic rates. Metabolic heat is both sensible and latent (evaporative or perspiration). Cockpit and cabin heat also is due to solar heating through canopies, windows and windshields; aerodynamic heating through external surfaces; and electrical and electronic equipment within the cockpit and cabin. Cabin heat loads vary considerably depending on aircraft size, speed, and internal equipment heat dissipation. Heat rejected from the hydraulic and avionic systems may add to the compartment heat load. Typical cockpit and cabin heat loads of different aircraft types are shown in Table 2.

4.2 Electronics Heat Source

Electronic components in avionic equipment are limited to minimum and maximum semiconductor junction, insulation and magnetic material operating temperatures which depend on the class of equipment. Commercial, Industrial and Military class equipment are all installed in current military aircraft applications. The thermal management system should be designed for the specific class of equipment it is servicing.

Avionics units are cooled with air or with liquid. In the early 1980s most avionics were being cooled with air as discussed in Franklin and Leonard (1983). Generally, however, liquid cooling is becoming a more accepted practice, especially in high power systems, such as long-range radars and electronic-counter measures (ECM), are cooled with liquid. More avionic systems are being cooled with liquid to maintain lower maximum component temperatures to reduce equipment failure rates and improve system reliability (Letton, 1979). The type of equipment cooling approach employed is dependent on avionic component temperature limits, temperature shock tolerance, equipment packaging density, heat dissipation rate, duty cycle, and reliability requirement. Avionic equipment is normally located throughout an aircraft, in pressurized compartments and in unpressurized areas such as radomes, wheel wells, fairing compartments, and external pods on aircraft. Air-cooled avionic equipment in large transport aircraft normally is located within a pressurized compartment. The avionic equipment heat may be rejected to the cabin environment, or it may be rejected as a heat load in a separate compartment (pressurized or unpressurized). Special mission aircraft may have dedicated cooling systems and heat sinks for mission equipment.

Avionic cooling requirements depend upon temperature limits of the equipment being cooled. For air-cooled avionics, flow rates between 2 to 10 lbm/min per kW (0.015 to 0.075 kg/s per kW) are used. The low rates are used normally if cold, dry air is available, and higher flow rates are needed if air supply is hotter and maximum allowable electronic part temperatures are low. For liquid cooled avionics, flow rates range from 3 lbm/min per kW (0.023 kg/s per kW) for water-glycol mixtures to 6 lbm/min per kW (0.045 kg/s per kW) for coolants such as polyalphaolefin (PAO). More information about the specific requirements and solutions can be found in AIR1277 and AIR64.

Power electronic equipment is a concentrated heat load that requires active cooling.

Permanent-magnet electrical motors generally require power electronic motor controllers for startup and control of inrush current, and to control motor speed.

These motor controllers contain solid-state switches (usually a type of bipolar transistor). Motor controllers also usually contain input and output filtering. Filtering devices can be passive (inductors and capacitors) or active (digitally controlled semi-conductors). Motor controllers also contain digital electronic elements that control and monitor power electronics and communicate with other aircraft systems. All the parts listed above are temperature limited and may require active cooling.

Power electronics can be air cooled or liquid cooled. For aircraft applications, air-cooled power electronics are currently not practical above a rating of approximately 10 kW due to spatial considerations and limitations on available cooling air. Liquid cooled equipment requires a cooling system that circulates a liquid coolant. The heat sink for the coolant is typically ram air, with provisions for inducing air flow for static conditions. The coolant is usually circulated by means of a pump, which itself will also be a heat source.

4.3 Bleed Air

Engine bleed air is used as an air source for a number of aircraft utilities including air cycle cooling systems, airframe and radome anti-ice systems, pneumatic systems, and On-Board Inert Gas Generation Systems/On-Board Oxygen Generation Systems (OBIGGS/OBOGS) systems. The bleed air is extracted from one or more stages of the compressor section of the turbine propulsion engines. The bleed air temperature varies with compressor design pressure ratio, compressor efficiency, engine power setting, altitude and ambient temperature. Bleed air temperatures for current design aircraft can range up to 1,250 °F (675 °C). For most applications, this air needs to be cooled to a lower temperature before it is supplied to the using system. An air-to-air heat exchanger (pre-cooler) near the engine can be used to reduce the bleed air to a temperature which allows more convenient ducting materials or will reduce potential airframe damage in the event of a large bleed air leak. Ram air or fan air is typically used as the heat sink for pre-coolers and ram air is also used for ECS heat exchangers downstream. Fuel has been used as an additional heat sink on supersonic aircraft where ram air stagnation temperatures are too high for sufficient bleed air-cooling.

4.4 Vapor Cycle Refrigeration

A vapor cycle refrigeration system is a heat pump that absorbs heat from its cooling load and rejects this heat plus the heat of compression at a higher temperature through the condenser. The capacity of a given vapor cycle system is inversely proportional to the temperature difference between the condenser and evaporator. (The selection of the refrigerant is driven by the heat sink available, cooling capacity and coolant supply temperature desired.) Ram air is the common heat sink for aircraft vapor cycle systems, except for high performance military fighters (e.g., F-22), where the cold air supplied from the ECS is used as an intermediate heat sink. The main sources of heat on VCS are fans and compressors.

4.5 Mechanical Power Systems

Mechanical power systems that may need cooling include hydraulics, flight control actuation, electric motors and accessory drives. Hydraulic systems typically operate with hydraulic oil temperatures as high as 250 °F (121 °C). However, steady state design point temperatures are more typically 160 to 200 °F (71 to 93 °C). For example, in one typical transport aircraft there are four separate hydraulic systems. Each system contains two engine-driven hydraulic pumps, each rated at 60 gpm (4.4 l/s) and 3,000 psia (20.7 MPa). Each system rejects 132,000 Btu/h (38.7 kW) at 10 gpm (0.73 l/s) case drain flow and 250 °F (121 °C) oil temperature. Hydraulic systems typically are designed for a baseline steady state heat load and an intermittent peak heat load.

Accessory drives are typically cooled by lubrication oil. Oil temperatures at the outlet of the accessory drive are typically 275 °F (135 °C). Electro-Mechanical power components number and dispersion throughout the vehicle typically increase with the trend to more electric aircraft.

Electric motor driven hydraulic and liquid cooling system pumps can be located throughout the aircraft as loads, interconnecting plumbing and service access allows. Thermal management is typically accomplished through the use of the pumped fluid to transfer the heat to the fluid heat sink. The temperature range of the fluid of -65 to 300 °F (-54 to 150 °C) is normally within the operating temperature range of the electric motor components.

Electro-hydraulic and electro-mechanical actuators for flight control actuation places these components in remote locations such as outer wing sections and fuselage tails. Access to heat sinks that are reliably available throughout the flight and operating condition envelope can provide a challenge. Installation ambient temperatures can range from the low temperatures seen during high altitude cruise to an increase over local ground ambient temperatures due to solar and self-heating inputs. Potential candidate heat sink locations include installation compartment, if ventilated, skin surface and fuel tanks. Locally installed control and power electronics can narrow the allowable EHA or EMA operating temperature range.

Typical design temperature considerations for initial heat sink matching to heat sources are found in Table 1:

Table 1 - Typical characteristics of several airborne heat sources

Heat Source	Coolant	Design Temperature Considerations
Cabin/Cockpit (Occupied Zone)	Air	Human Comfort (typical area temperature 59 to 86 °F (15 to 30 °C), typical supply temperature 32 to 158 °F (0 to 70 °C))
Avionics	Air	Minimum supply temperature above the dewpoint (less than 100% R.H.) for moisture sensitive equipment Maximum supply temperature is equipment specific
Avionics	Liquid (EGW, PGW, PAO, etc.)	Minimum liquid temperature typically 50 to 68 °F (10 to 20 °C) with fluid viscosity and condensation as considerations. Maximum supply temperature is equipment specific.
Engine Bleed Air	Air	Wide variation of bleed air temperature (up to 1,250 or 675 °C) Ram air stagnation temperature
Vapor Cycle Condenser	Air or Liquid (Fuel)	Refrigerant condensing temperature typically needs to be a minimum of 18 °F (10 °C) above heat sink temperature Condensing temperature dependent on refrigerant selection and maximum system pressure ¹
Mechanical Power Systems	Air or Liquid (Fuel)	Oil Temperature (typical -40 to 275 °F (-40 to 135 °C)) Fuel Temperature is upward limited by maximum allowable fuel temperature at the engine interface
Electrical Power Systems	Air or Liquid	Minimum supply temperature above the dewpoint (less than 100% R.H.) for moisture sensitive equipment Maximum supply temperature is equipment specific
Fuel	Air	Maximum allowable fuel temperature
Weapons (DEW)	Liquid (EGW, PGW, PAO, etc.)	Application Specific

¹Condensing (or evaporating) temperature and pressure are interrelated for a given refrigerant. Which variable is the dependent variable and which is the independent variable depends on the application limitations. For example, the heat sink temperature may set the condensing temperature with a resultant condensing pressure. However, if an evaporating temperature (and pressure) is required by the application, and the compressor pressure ratio is limited by design considerations (like available power), then the condensing pressure is fixed, with a resultant condensing temperature for the selected refrigerant. The design will have to provide a suitable heat sink which temperature is lower than that condensing temperature.

4.6 Electrical Power System

Electrical power systems are a source of waste heat generation for aircraft. The electrical power systems include equipment for power generation, wiring and equipment needed for distribution of electrical power to the aircraft electrical loads.

4.6.1 Power Generation

Power generation includes electrical generators and generator drive systems. Generators are typically driven by main engine accessory gearboxes and auxiliary power units. Generators require cooling. The upper temperature limit of generating equipment is generally based on the insulation on wire-wound stators and rotors, and magnet material in permanent-magnet generators.

Generators are typically oil-cooled but can also be air-cooled. For oil-cooled generators the oil is often shared with the gearbox to which the generator is attached. The oil in turn is generally cooled with a liquid-to-air heat exchanger.

Generators can be variable-frequency or constant-frequency. Constant-frequency machines use a constant speed drive (CSD) transmission that is usually combined with the generator to form an integrated drive generator (IDG). In an IDG, the lubricating oil for the transmission also serves to cool the generator. This oil then rejects heat into a dedicated cooler (typically a liquid-to-air heat exchanger) or the IDG can share its oil with the engine accessory gearbox to which it is mounted. Variable-frequency machines do not have a transmission so the only heat source is the generator itself.

4.6.2 Power Distribution

Electrical power is distributed from the generators to the loads via a network of wiring and switching devices. Electrical wiring is an aircraft heat source that is a function of electrical resistance and current being carried. Switching devices are used to isolate or connect generation sources to aircraft electrical buses, and connect or isolate loads to the various buses. These switching devices can be either electro-mechanical or solid state. The switching devices are generally located on electrical panels, and therefore these panels can require active cooling. The cooling medium is generally air.

4.7 Engine and APU

Engine heat sources include controls, actuators, structure, and lubrication. Controls operate at lower temperatures than engine structure. The controller uses electronic components with temperature limits much the same as those in airframe avionics. Hydraulic actuators that are fuel cooled or use fuel as the working fluid operate at temperatures well below the coking temperature of the fuel which is about 300 to 350 °F (149 to 177 °C) for traditional kerosene base fuels. Pneumatic actuators can operate much hotter at temperatures above 1,000 °F (538 °C). While nozzles of some afterburning turbojets may be cooled for supersonic military aircraft, the structure heat load of engines for hypersonic aircraft can become very large, as discussed in Coons (1986). Heat generated by the lubrication system typically is rejected with oil temperatures limited to 225 °F (107 °C). Engine high pressure bleed air may be used for internal engine cooling however the cooling of this air to usable temperatures can be a large heat source.

4.8 Fuel

Fuel is commonly used as a heat sink for other systems but may require a heat sink itself if temperatures can exceed maximum allowable fuel temperature. In some fighter aircraft, fuel flowing to the engine is used as heat sink for power systems. The fuel flow rate from the tanks may be increased to be greater than required by the engine in order to provide sufficient local heat sink capacity to all heat exchangers. Fuel flow in excess of that required to meet current engine power demands is recirculated back to one or more of the fuel tanks. The returned fuel may be cooled by a ram air heat exchanger prior to return to the fuel tank to reduce fuel temperature in the tank. Some aircraft require minimum operational fuel levels based on the heat transfer rate from the fuel to the airframe and subsequently to the ambient air. These transfer rates decrease with decreasing fuel level.

4.9 Example Heat Loads

Typical cockpit and cabin heat loads of different aircraft types are shown in Table 2. The loads are estimated values or derived from published design data. The methods to obtain the figures may differ, resulting in different heat load values for similar listed heat load areas. The heat load for a specific aircraft and mission should be measured or estimated in detail to establish cooling system requirements. More information about cabin and cockpit heat sources can be found in AIR1168/3.

**Table 2 - Sample aircraft cabin or cockpit heat loads
compiled from multiple sources with multiple assumptions**

Not for relative comparison

Aircraft Type	Heat Load Area	Heat Load (Btu/h)	Heat Load (kW)
Military Fighters			
	Crew	400	0.12
	Avionics	4,700	1.37
	Electrical	1,700	0.51
	Heat transfer through structure	9,000	2.64
	Solar heat load	8,000	2.36
	Avionics Cooling Fan	7,200	2.10
	Total	31,000	9.10
Military Surveillance - Large transport			
Cockpit	Crew (3)		
	Occupant heat load	1,200	0.35
	Electrical Heat Load	3,300	1.00
	Solar Heat Load	600	0.16
	Structural Heat Load	-5,200	-1.50
	Cabin		
	Occupants (19)		
	Occupant heat load	5,200	1.50
	Electrical Heat Load	158,200	46.40
	Solar Heat Load	2,900	0.85
	Structural Heat Load @ Mission Altitude	-84,800	-24.80
Military Surveillance - Business Jet			
Cockpit	Crew (2)		
	Occupant heat load	800	0.23
	Electrical Heat Load	10,100	3.00
	Solar Heat Load	1,100	0.33
	Structural Heat Load	-5,200	-1.55
	Cabin		
	Occupants (8)		
	Occupant heat load	2,200	0.64
	Electrical Heat Load	143,500	42.0
	Solar Heat Load	0	0.00
	Structural Heat Load @ Mission Altitude	-17,000	-5.00

**Table 2 - Sample aircraft cabin or cockpit heat loads
compiled from multiple sources with multiple assumptions (continued)**

Not for relative comparison

Aircraft Type	Heat Load Area	Heat Load (Btu/h)	Heat Load (kW)
Business Jet			
Cockpit	Crew (2)		
	Occupant heat load	1,228	0.360
	Electrical Heat Load	3,207	0.940
Cabin	Solar Heat Load	3,958	1.160
	Occupants (8)		
	Occupant heat load	1,774	0.520
	Electrical Heat Load	4,282	1.255
	Solar Heat Load	9,537	2.795
	Total	23,986	7.030
Military Helicopters			
Combat Helicopter	Crew (2)	1,100	0.34
	Cabin electronics	6,800	2.00
	Heat transfer through structure	3,400	1.00
	Leakage	1,700	0.50
	Solar heat load	6,800	2.00
	Total	19,800	5.84
Naval Helicopter	Crew (3)	1,700	0.5
	Cabin electronics	34,100	10.0
	Heat transfer through structure	13,700	4.0
	Leakage	9,400	3.0
	Solar heat load	9,400	3.0
	Total	68,300	30.5
Civil Airplane Transports			
Cockpit	Crew (2)		
	Occupant heat load	500	0.17
	Electrical heat load	4,600	1.34
	Solar heat load	5,200	1.53
Cabin	Total	10,300	3.04
	Occupants (317)		
	Occupant heat load	82,000	24.0
	Electrical heat load	76,000	22.3
	Solar heat load	22,900	6.7
	Total	180,900	53.0