AEROSPACE INFORMATION REPORT

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Superseding AIR1957

(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

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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 AIR1277and 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

[1]Condensing (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
	Solar Heat Load	3,958	1.160
Cabin	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	Crew (2)		
Cockpit	Occupant heat load	500	0.17
	Electrical heat load	4,600	1.34
	Solar heat load	5,200	1.53
	Total	10,300	3.04
Cabin	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

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/hr)	Heat Load (kW)
Civil Helicopters			
Light twin helicopter	Crew heat load (2)	1,200	0.34
	Occupant heat load (5)	2,000	0.60
	Cabin electronics	2,000	0.60
	Heat transfer through structure	5,100	1.50
	Leakage	1,400	0.40
	Solar heat load	6,800	2.00
	Total	18,500	5.44
Transport helicopter	Crew heat load (3)	1,700	0.50
	Occupant heat load (27)	11,100	3.24
	Electronic Heat Load	17,100	5.00
	Heat transfer through structure	13,600	4.00
	Leakage	10,200	3.00
	Solar heat load	10,200	3.00
	Total	63,900	18.74

5. HEAT SINK SYSTEM DESIGN OBJECTIVES

There are two general requirements for heat sink design. The first is to match the capacity of the heat sinks to the temperature and heat transfer rate of the heat sources. The second is to optimize the design to minimize aircraft impact. In addition, the requirements for heat sink design include high reliability, easy maintenance, and high damage tolerance. These items impact the aircraft's ability to meet mission cycle requirements, which are important for both military and commercial aircraft. Heat sink design objectives are summarized in Table 3.

Table 3 - Heat Sink Design Objectives Summary

Objectives	Factors
Match heat sinks to heat sources	Temperature and power capacity of available heat sinks Temperature and power of heat sources Duty cycles and soak back of heat sources and sinks Available aircraft power Resulting design conditions Consider growth capability
Optimize systems to minimize overall aircraft Impact	Weight/drag impact on aircraft performance Power extraction effect on engine performance Cost of ownership (procurement/maintenance/logistics)
Maximum component reliability	Failure rates Need for redundancy Operating and storage life
Minimize systems maintenance	Accessibility Operational test capability (built in test and other failure detection) Corrective maintenance
Systems Safety	Primary and secondary damage effects
Minimize system and aircraft damage	On heat sink related systems On other aircraft systems Due to enemy threats

5.1 Heat Sink and Source Matching

Guidelines for matching heat sources and heat sinks, and factors to be considered in selecting systems that transport heat between them, are reviewed in this section.

Optimum matching of heat sources and heat sinks requires determination of heat source and heat sink characteristics as a function of aircraft operating parameters. These parameters include ground operations, flight time, speed, altitude and mission (commercial, military, transport, fighter, helicopter, etc.).

Other required characteristics are:

- heat source heat rejection rate and operating temperature;
- temperature limit, capacity, and availability of heat sinks;
- duty cycle or flight profile in which the system will operate;
- type and quantity of power available to operate the system.

Examination of these data usually leads to several specific operating conditions that become the critical design points for the system.

5.2 System Optimization

Different methods for transferring heat from sources to sinks should be compared in the process of varying system parameters for optimized aircraft performance. Weight, power usage, complexity, and cost are all parameters to be considered.

A key parameter used in optimization trade-off studies is the aircraft takeoff gross weight (TOGW) penalty. The TOGW penalty has a strong impact on aircraft performance and operating cost.

The impact of each system on TOGW requires determination of:

- weight of the installed system and the increase in the weight of structure or other equipment required to support the system;
- fuel weight necessary for system power (extracted from aircraft engine or APU);
- fuel weight necessary to carry the weight of the equipment, increased structure or equipment to support the equipment and fuel;
- fuel weight necessary to overcome the aerodynamic drag increase due to ram air use in heat exchangers.

The sum of these parameters is the TOGW penalty of the system. TOGW analyses provide insight into the system impact on aircraft fuel economy or operating range. It should be noted that penalties for power sources (engine bleed air or shaft power extraction), ram air usage, and weight induced drag vary significantly with aircraft type, the engines used, and flight speeds and altitudes.

Another very useful optimization comparison is system cost. It is the total cost of ownership for the system configuration. It includes procurement cost for initial system hardware and its installation, maintenance requirements and their costs, and spare costs based on expected useful equipment life.

5.3 Reliability

The choice of specific heat sink, identified in Section 6, impacts the system reliability. The reliability of a heat sink, as of any other system component, is related to it failures modes and how does it affect the system overall failure rate and consequent availability for the system to perform its function. Normally a system specification demands the requirements from where the type, shape, location and other general design characteristics are defined. The following are examples of failures that should be considered when designing heat sinks:

- ambient air (ram air): hail, volcanic ash, ram air door, ducts, sensors, fans, ejector;
- fuel: leaks in a liquid to liquid heat exchanger, pump, valves;
- expendables: leaks, valves;
- thermal storage: leaks, valves;
- ECS coolant: fluid leak, fans, compressors, sensors, ducts, pumps, ACM issues;
- fan air heat sink: FOD, leaks, fans.

5.4 Maintainability

Heat sink system design should include requirements for easy maintenance. Maintenance requirements include maximum component accessibility, especially fill and drain ports, cleaning of heat exchangers and ram circuits, skin surface and fuel heat exchange surfaces for optimum heat exchange, fluid replenishment (liquid loops) and safety of maintenance personal (blade guards, noise, etc.).

Provision for built-in-test (BIT) and fault isolation may be required to indicate potential failures and out-of-tolerance performance or to isolate failures that have occurred. Sensing of critical system performance parameters is possible as Maintenance messages due to filter clogging.

5.5 System Safety

The typical system safety process includes a failure mode, effects and criticality analysis (FMECA) to evaluate the effects and consequences of possible damage on flight essential functions. Primary and secondary damage effects on each component should be identified, and the impact on the system in terms of total failure, or degraded performance, should be quantified. Examples of system failures and respectives effects particular to heat sinks are:

- heat sink ducting might be affected by HX failure;
- ground deice fluid ingestion through ram air circuits;
- location of fuel and hydraulic drains respective to heat sink inlets;
- fluid leakage can provoke fire in the HX;
- monitoring of outlet circuit for high temperatures and automatic system shutdown;
- alternate or backup heat sink on critical load systems;
- bird strike.

6. HEAT SINK TYPES

Characteristics, capabilities and limitations of the different types of heat sinks are discussed in this section.

A key characteristic in the classification of heat sinks is the duration of their use. Extended duration heat sinks include ram air and fuel; shorter duration heat sinks are expendable liquids and thermal storage materials.

6.1 Ambient Air

Ambient air can be utilized as a heat sink in two ways: ducted into the aircraft as ram air or used to transfer heat directly from the fuselage.

6.1.1 Ram Air

Ram air is used as a heat sink in many aircraft. Typically, the heat of compression of the working fluid is rejected to the environment via a heat exchanger. The heat exchanger is usually installed in a non-pressurized area to avoid large ram duct penetrations into a pressurized compartment. Ram air can be introduced into the heat exchanger via protruding ram scoops, flush (NACA) inlets. The stagnation temperature of the air at worst case conditions should be used for initial system design calculations. Local pressure coefficients (C_p) and ram recovery factors (R_f) must be obtained to calculate the true ram recovery pressure, which can be significantly less than the free stream total pressure. When using protruding scoops, avoid locating the inlet in the boundary layer, as this will reduce ram flow performance. Ram inlet ducts must be designed to withstand high air velocity and acoustic vibration and may require turning vanes to ensure proper flow distribution across the face of the heat exchanger. Ram outlets should incorporate exhaust louvers or a shroud to assist in turning the exhaust flow into the ambient air stream, thereby reducing exit pressure losses. Plume impingement on the outer skin must be quantified to determine if a steel or titanium "patch" is needed to prevent damage to the aluminum or composite skins. The plume analysis will also be used to determine the effect on the aircraft IR signature. The use of ram air results in drag penalties from the inlet/exhaust flow disturbances (external drag) and from a change of air speed and direction in the ram duct (internal drag).

6.1.2 Skin Convective/Conductive Heat Transfer

When the ambient air recovery temperature is below the desired cabin temperature, the aircraft fuselage can be used to reject heat directly to the environment using skin convective/conductive heat transfer.

6.1.2.1 Skin Convective/Conductive Heat Transfer Using Air Loop

The overall heat transfer coefficient (U) must be increased as high as practical to improve heat transfer from the cabin to the environment. The skin external heat transfer coefficient (ho) is very large compared to the internal heat transfer coefficient (hi) and skin conductivity. Therefore, any effort to improve the external coefficient will have diminishing returns. Insulation inside the cabin can be removed to increase the conductivity through the skin. However, when doing this two important factors must be considered; (1) During low altitude operation, where the ambient recovery air temperature is above the desired cabin temperature, the heat transfer into the cabin will increase and (2) The inner skins, frames, and stringers may "sweat" from condensation upon aircraft descent to lower, more humid altitudes. Excessive corrosion to cabin substructure can result and efforts should be made to dry the cabin air so that its dew point is below the expected inside substructure temperature. Air barriers/liners should be attached to the aircraft frames, separating the cabin from the skins where a fan circulates dry air through the air barrier and air distribution ducts to improve the internal convective heat transfer coefficient (hi) (see Figure 1).

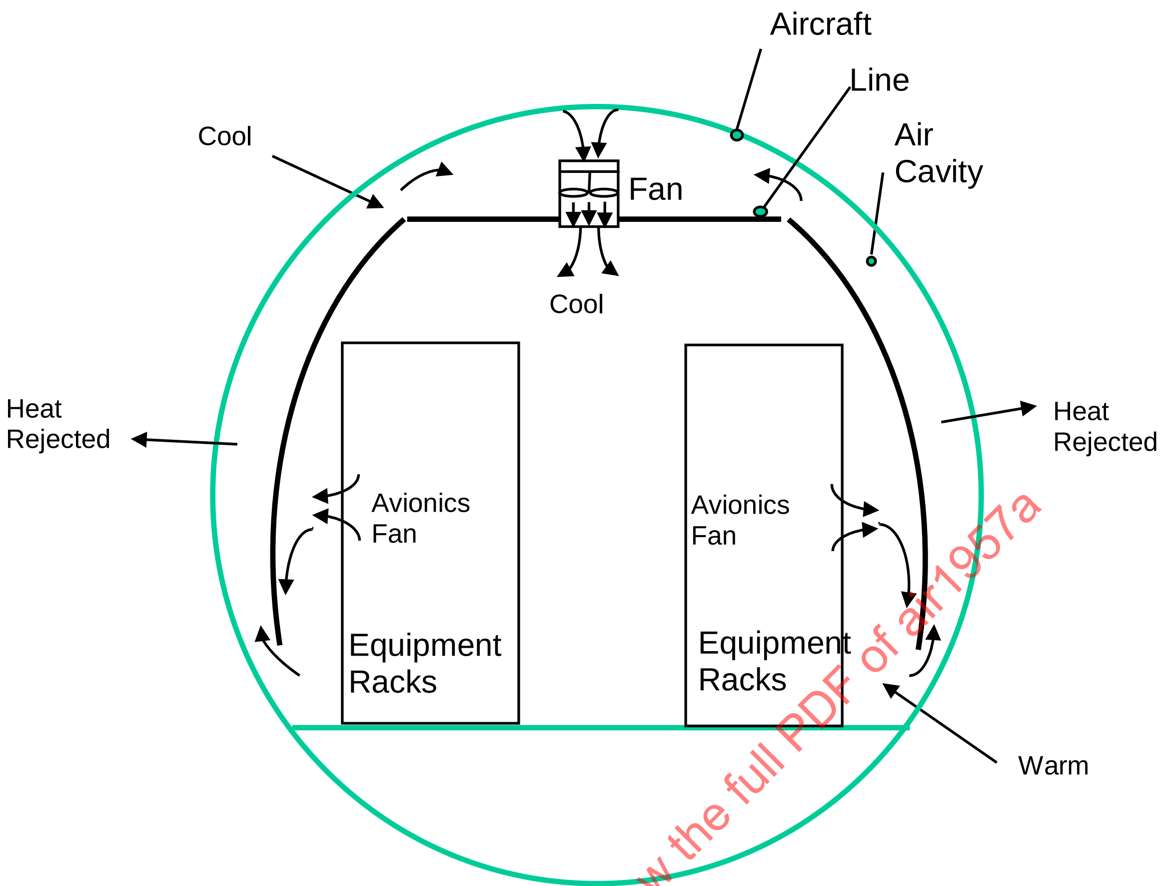

Figure 1 - Skin convective cooling with fan (space saver)

Skin heat exchangers can be used in lieu of airflow directly over internal skin surfaces to further increase heat transfer efficiency and minimize the area of uninsulated substructure. One such alternative system, shown schematically in Figure 2, uses avionics compartment exhaust air as a heat transfer medium and the aircraft internal skin surface as the heat sink. Pressurized air from an avionics suction manifold is circulated through the cavity between the compartment liner and the fuselage inner skin surface. A contoured liner, comprised of flexible interlocking sections, is configured to maintain a constant, thermodynamically optimal airflow passage height.

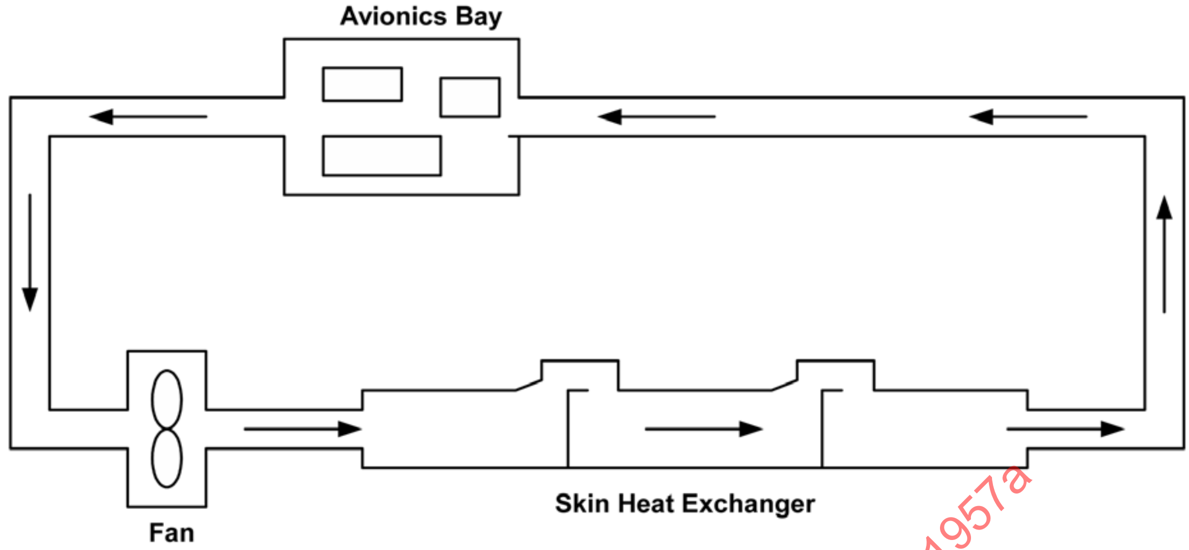

Figure 2 - Air-to-air skin heat exchanger

Using air as the heat transfer medium presents limitations to the overall system efficiency and operational envelope. Air has a low specific heat per unit volume, consequently, large temperature changes are required in air-to-air heat exchange systems to achieve satisfactory performance. Overall skin heat exchanger effectiveness can be improved with the addition of plate-fin elements bonded directly to the inner skin surface with conductive epoxy. The fins provide increased convective heat transfer surface area while inducing turbulence. In situations where the ambient temperature and flight parameters would otherwise fail to provide adequate skin temperatures, conditioned air augmentation may be required to provide supplemental cooling along with provisions for venting hot avionics exhaust air overboard.

6.1.2.2 Skin Convective/Conductive Heat Transfer Using Liquid Loop

An alternative skin heat exchanger configuration using liquid as the heat transfer medium is shown schematically in Figure 3. Liquids have significantly higher heat capacity per unit volume than gases. Moreover, the inside film heat transfer coefficient, typically on the order of 5 to 10 Btu/(h.ft^2.R) (30 to 60 W/(m^2.C)) for air systems, is much higher for liquid systems (typically 20 to 60 Btu/(h.ft^2.R) (100 to 350 W/(m^2.C)). Consequently, total heat exchanger surface area is reduced.

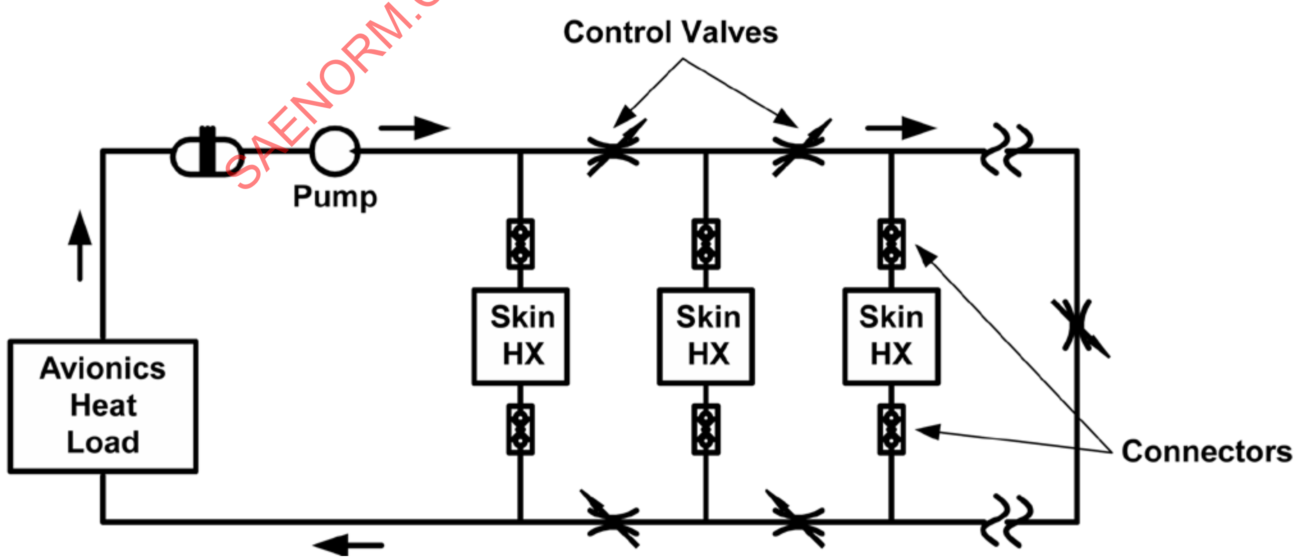

Figure 3 - Liquid-to-air skin heat exchanger

The modular liquid coolant heat exchanger system cross-section, shown in Figure 4, is compatible with semi-monocoque fuselage design, and incorporates an arcuate planar heat sink with integral liquid coolant circulation pathways.

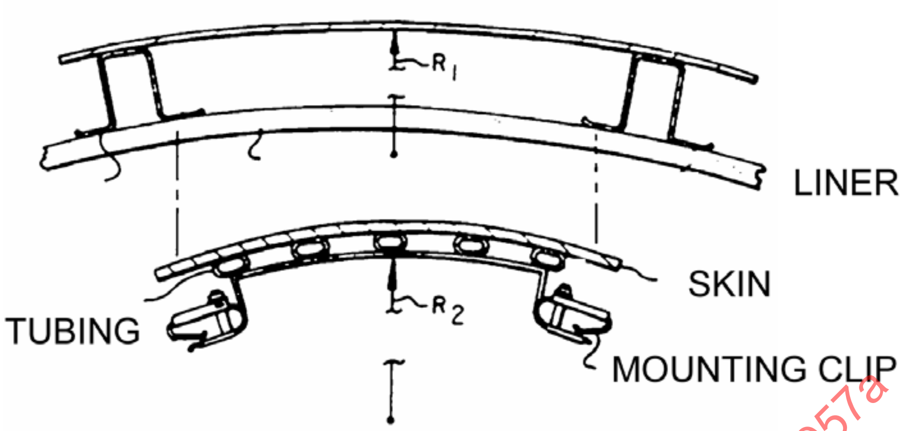

Figure 4 - Liquid-to-air skin heat exchanger cross-section

Liquids suitable for this configuration include ethylene glycol/water, propylene glycol/water, or polyalphaolefin (PAO). As with air-to-air systems, however, cooling augmentation may be required if ambient conditions fail to provide adequate skin heat sink temperatures (ref. US Pat. No. 4,819,720 issued to Howard, US Pat. No. 5,702,073 issued to Fluegel).

6.1.2.3 Skin Convective/Conductive Heat Transfer Using Heat Pipe

A heat pipe offers the advantage of high heat transfer coefficients of liquids, but without the need for a liquid pump. This concept adds an evaporator to absorb heat from the cabin or avionics via a fan loop and transfer it to the condenser (skin heat exchanger) (see Figure 5). An even more efficient system integrates individual evaporators directly in the immediate vicinity of the heat source, negating the need for a fan loop.

6.2 Engine Fan Air Heat Sink

Air from a turbofan engine is a commonly used heat sink. One advantage of using fan air is that the engine fan air is available any time the engine is running. Thus, ground fans or ejectors are not needed to induce heat sink air flow during ground static operation. A disadvantage of using engine fan air is the impact on engine thrust. There are two methods of implementing an engine fan air heat sink: (1) fan air ducted to a separately mounted heat exchanger, and (2) fan duct heat exchangers.

6.2.1 Separately Mounted Heat Exchanger

In this implementation of engine fan air as a heat sink, fan air is extracted from the engine fan via a port downstream of the engine fan prior to the discharge nozzle. The air is ducted to the heat exchanger. The heat exchanger is often located near the engine upstream of the engine firewall and is used to cool engine bleed air. In this embodiment, the heat exchanger is termed a precooler. A valve is usually used to modulate the fan air to control temperature of the hot side stream and to minimize the penalty associated with the use of fan air.

6.2.2 Fan Duct Heat Exchanger

Heat exchangers may be imbedded inside the engine fan duct and use fan air as the heat sink. Benefits associated with this concept are a corresponding reduction in the use of ram air heat exchangers, thus reducing the penalties in aircraft drag. Additional benefits of fan air heat sinks are low observability (reduced infrared signature) and addition of heat energy to the fan duct stream. However, fan air temperatures are generally somewhat higher than the ram air temperature. Therefore, fan duct heat exchangers may not be as efficient and could get heavier, particularly if high temperature materials have to be used for their fabrication. The heat exchangers also add to the pressure drop in the engine fan duct, reducing engine thrust. Airframe companies have to make their assessment of fan duct heat exchangers at the air vehicle level for any given aircraft.

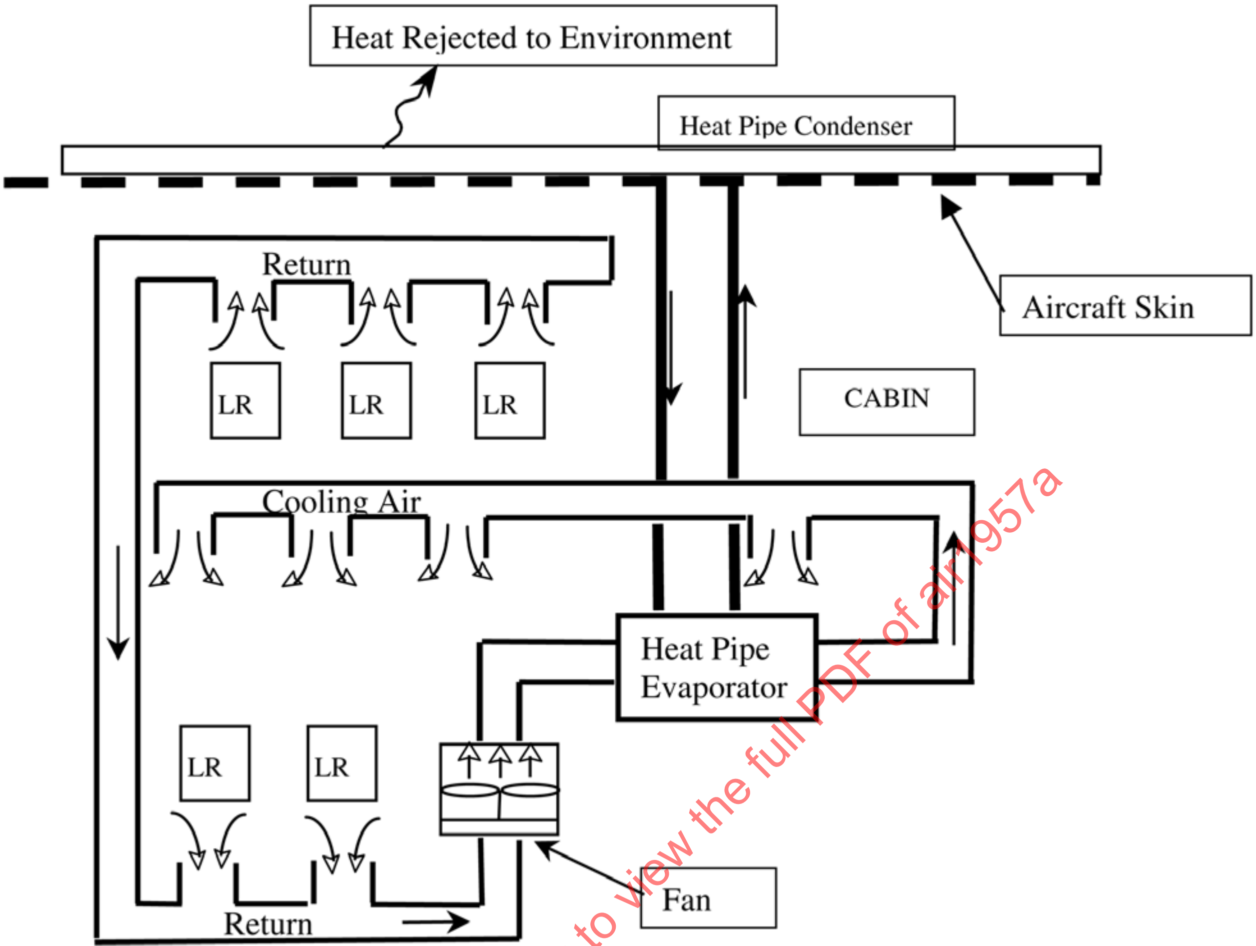

Figure 5 - Skin convective cooling with heat pipe

6.3 Fuel

Fuel is used as a heat sink in most turbine engines and for many airframe heat sources, is readily available and presents a low penalty factor (or sometimes a benefit) to the aircraft. However it is important to consider the overall impact to the aircraft.

There are two basic methods of implementing fuel heat sinks. In one method, fuel that is being delivered to the main powerplant or APU to be consumed, is typically passed through a fuel/oil heat exchanger which has the dual purpose of cooling the engine oil while raising the temperature of the fuel being delivered to the fuel nozzles. The increase in fuel temperature results in improved engine efficiency.

The other method of fuel heat sink utilization is where heat is transferred from aircraft systems into the fuel in the fuel tank. One example of this method is using a fuel/oil heat exchanger as described above except that the fuel flow is greater than the fuel consumed by the engine - in this case the warmed fuel that is not used by the engine is recirculated back to the tank. Another example involves placing a heat exchanger in the fuel tank whereby a systems fluid (such as hydraulic fluid) transfers heat directly into the fuel tank.

Transferring heat into the fuel tank will result in increased fuel tank temperatures. The temperature of the fuel has an influence on fuel tank flammability. The impact on fuel temperature and fuel tank flammability should be evaluated when considering using fuel as a heat sink.

At the aircraft level, the impact of fuel heat sink utilization includes the weight of components and controls needed and the unusable fuel in added fuel lines and heat exchangers or minimum fuel requirements if recirculation to tank is used. There is no drag penalty associated with a fuel heat sink, unless it is cooled by ram air by a heat exchanger. The capacity of fuel as a heat sink is limited by the type and amount of fuel available and by engine and fuel tank limitations as described in AIR1812 and Wiese (1991). Higher speed aircraft which may use cryogenic fuels will have both greater heat sink capacities, due to lower fuel temperatures, and greater heat sink requirements, due to greater heating at the higher speeds, as described by Coons (1986). Fuel heat sink capacity is limited at the end of the flight simply because the fuel consumption during the flight has reduced the quantity of fuel available and reduced effective heat transfer area of the fuel tank walls.

An alternative method to using fuel as a heat sink will be required if heat sink capability is required on ground when the aircraft is stored in confined areas such as the hangar deck of an aircraft carrier. The heating of the recirculating of the fuel will result in the venting of fuel vapors which would be a safety as well as a health hazard in the confined space.

6.4 Expendables

Expendable heat sinks, typically used in spacecraft and special mission aircraft, utilize the latent heat of vaporization of stored, expendable liquids, which after vaporizing are vented to the atmosphere. These heat sinks typically handle peak or short duration loads for selected portions of a flight envelope, since their weight is almost directly proportional to duration of use. Expendable heat sink capacity is calculated as the product of the mass of liquid used and the latent heat of vaporization of the liquid. To be of value, the expendable boiling point temperature of the heat sink must be below the limiting temperature of the heat source being cooled. Sensible heating of the liquid or vapor may provide additional capacity.

Limitations of expendables are the weight of the expendable liquid and its container, servicing and logistic requirements to provide adequate liquid for each flight, and corrosive or toxic properties of these liquids. If water is used, an antifreeze solution must be added or reservoir and plumbing heaters added. If antifreeze is added, the water-antifreeze container should be completely drained at the end of flight before refilling it in order to assure that the mixture is of the correct composition. Alternatively, a representative sample can be tested to determine the composition of the remaining mixture. This is necessary since water and antifreeze evaporate at different rates and the remaining mixture can be of unknown composition.

6.5 ECS Coolant

Liquid coolant such as those provided by an air or vapor cycle refrigeration system, may be used directly as the heat sink, indirectly as a heat sink via use of intermediate loops or from ECS exhaust from other heat loads. Refrigeration cycles offer capability to cool a heat source to temperatures below the temperature of an available heat sink, using power to pump heat up to the hotter heat sink.

A limitation on the use of ECS or refrigeration system air is that it imposes a power penalty on the engine. An air cycle system uses bleed air from the engine or from a separate compressor. Electrical power, via a power takeoff shaft, powers most vapor cycle refrigeration systems. The power use increases engine fuel consumption and decreases engine thrust. If air used for cabin or cockpit cooling and pressurization is then used for cooling of another heat source, it will have small additional aircraft penalties. However, the temperature range of heat sources cooled by ECS air is higher because it has previously been used for another heat load.

6.6 Thermal Storage

Thermal storage heat sinks may consist of phase change, non-expendable materials, or the aircraft structure. Their duration of use is limited, and their heat sink capacity per unit weight generally is less than for expendables.

Phase change materials generally provide an added sink during limited portions of the flight envelope, when the normally used heat sink temperature is too high. The thermal storage heat sink temperature is the melting point of the material, assuming that the heat capacity of the material is not exceeded. Thermal storage materials normally are solids which melt to provide the heat sink capability. Major physical properties of thermal storage materials are high thermal capacity and high latent heat of fusion. Disadvantages of phase change materials are the weight of the material and its heat transfer device, gradual degradation of thermal physical properties of some materials, and added maintenance. High thermal power may require design considerations to mitigate the typical poor thermal conductivity of phase change materials.

Aircraft structure may become the heat sink for short time transient heat loads. Heating of structure should not cause it to exceed safe temperature limits. Advantages of the structure as a heat sink are low weight penalty and no added maintenance.

7. HEAT SINK DESIGN

7.1 Heat Transfer to Heat Sinks

Generated heat may be transferred directly or indirectly to a heat sink. Direct heat transfer occurs when a heat sink fluid flows adjacent to the heat generation source. Indirect heat transfer occurs when an intermediate fluid transport loop transfers heat from the heat source to the heat sink. Generally, heat exchangers are required for indirect heat transfer. Basic considerations for selecting the fluid heat transfer technique to cool heat sources, and examples of direct and indirect heat transfer designs, are presented in this section.

The sizes of fluid heat transfer system components, such as heat exchangers and fluid lines, are dependent on fluid flow rates, inlet temperature difference (ITD), allowable pressure drop, and physical properties of the fluids involved. Generally, lines are sized for fluid velocities resulting in turbulent flow. This results in better overall heat transfer coefficients and smaller, lighter components.

Convective heat transfer coefficients depend on the fluid used (air or liquid) and the heat transfer surface employed. Table 4 depicts five basic ranges of heat transfer coefficients. System pressure loss is an important sizing factor used to achieve these coefficients. For any systems, the pumping power that is required to force the fluid flow through the system is inversely proportional to the density of the fluid and directly proportional to the pressure loss of the heat transfer surface. For fluids whose density changes with altitude, such as air, the pumping power required can be very much greater at high altitude conditions.

Table 4 - Basic ranges of heat transfer coefficients

Coolant	Mode of Heat Transfer	Heat Transfer Coefficient (Btu/(h.ft^2.°F))	Heat Transfer Coefficient (W/(m^2.°C))
Air	Natural Convection	1 to 5	5 to 28
Air	Forced Convection	5 to 110	28 to 630
Liquid	Forced Convection	110 to 2,500	630 to 14,335
Liquid	Condensing	2,500 to 7,000[a]	14,335 to 40,140
Liquid	Evaporating	750 to 4,700[a]	4,300 to 26,950

[a] The coefficient ranges provided for the condensing and evaporating modes are dependent on fluid physical properties and driving temperature difference. The coefficients listed are for water. Use of other fluids will reduce these coefficients somewhat.

Important physical properties which affect system size are fluid specific heat capacity, thermal conductivity, and viscosity. If a phase change takes place in the system, the latent heat of vaporization or heat of fusion also are factors. The strength and weight of material used also must be considered.

Discussion of tradeoffs between different heat transfer means and area.

Optimum system heat transfer design involves using fluid properties to achieve the best system at a minimal penalty. Generally, weight, volume, and power consumption are major concerns. Further design information is found in AIR1168/3, AIR1811, and Kays and London (1984).

7.2 Ambient Air

The entire speed and altitude envelope of expected aircraft operations shall be evaluated when considering the use of a ram air heat sink. Density variations and temperature effects of adiabatic compression must be considered. The resulting system is sized for the most severe condition. It can be oversized for many conditions, and this imposes high penalties on the aircraft. However, controls that modulate the flow of air to minimum requirements reduce the adverse effects. The additional complexity of the controls should be traded against drag reductions.

The maximum Mach number of most aircraft flight envelopes initially increases with increasing altitude. Although ambient air temperature decreases as a function of altitude, the maximum stagnation temperature can increase as altitude increases due to the increasing maximum Mach No. of the flight envelope. This is evident by the following temperature - Mach No. relationship for air:

$$Tt = Ts[1 + 0.2M2] \qquad \text{(Eq. 1)}$$

where:

Tt = Stagnation or total air absolute temperature (K or °R)

Ts = Static or freestream ambient air absolute temperature (K or °R)

M = Mach number

Therefore, high ram air stagnation temperatures, as speed increases, may not provide heat sink temperatures low enough to satisfactorily cool the heat sources. If ram air temperatures are too high, a heat pump or refrigeration system may be considered to pump heat to the hotter ram air heat sink. Disadvantages of a heat pump are increased number of components, power consumption, more weight, and higher aircraft drag due to a larger ram airflow rate. More ram air flow may be needed to dissipate the added inefficiencies of the heat pump system unless the discharge temperature is increased. In many cases for military aircraft, only ram air is used on the ground and during subsonic and low supersonic speed operations. Other sinks, such as fuel or expendable liquids are used during the high-speed portions of the flights. High altitude/low indicated airspeed flight creates special design challenges since the low ambient air density will typically more than negate the advantage of low temperature.

Moisture condensed from air in a refrigeration unit sometimes is used to increase the effectiveness of a ram air heat sink in high ambient humidity conditions. Moisture enters the refrigeration unit as vapor and is condensed during air cooling. The condensed moisture is separated from the air by a water extractor, then is injected into the ram air cooling flow. When the moist cooling air passes through a heat exchanger, the condensed moisture is partially re-evaporated. The ram air capacity is now the latent heat of vaporized water plus the sensible heat of dry air. This heat sink feature is proportional to the available liquid water which normally decreases with altitude.

7.3 General Discussion of Subsonic Ram Air Intake Design

The large majority of all subsonic intakes can be divided into two categories. These are nose inlets and side inlets. Nose inlets include forward fuselage, wing nacelle, or wing pod configurations. Side inlets include wing root, scoop, and flush configurations.

As a general rule, successful intake design should consider the following objectives:

a. The inlet total pressure recovery should be the maximum attainable without unreasonable compromise in other areas.

b. Airflow distortion (unequal flow distribution) and associated drag penalties should be minimized.

Inlet total pressure losses associated with subsonic intakes can be divided into four broad categories. These are entry loss, diffuser loss, change-of-cross-section loss, and friction loss. Entry loss includes the combined effect of all losses involved in establishing axial, internal duct flow. These include internal separation losses due to high mass flow ratio or high angle of attack operation, entry friction losses, and scrubbing losses resulting from other aircraft components forward of the inlet. Thus, the principal entry effect is flow separation, which has traditionally required comprehensive 3-D flow field simulation tools and experimental data for accurate assessment.

Diffuser loss, the next major item contributing to inlet total pressure drop, represents a combination of separation and friction losses. For a given area ratio and intake Reynolds number, there exists an optimum wall divergence angle. Wall divergence angles greater than 15 degrees in any one plane and diffuser bends greater than 10 degrees should be avoided. However, when length considerations necessitate compromise, acceptable performance can be obtained with boundary layer control devices. These include vortex generators, suction slots, and injection slots.

Change of cross-section at constant flow area does not cause severe losses when the general rules of good duct design practice are carefully followed.

Two examples of ram air heat sink design are shown below in Figure 6 and Figure 7.

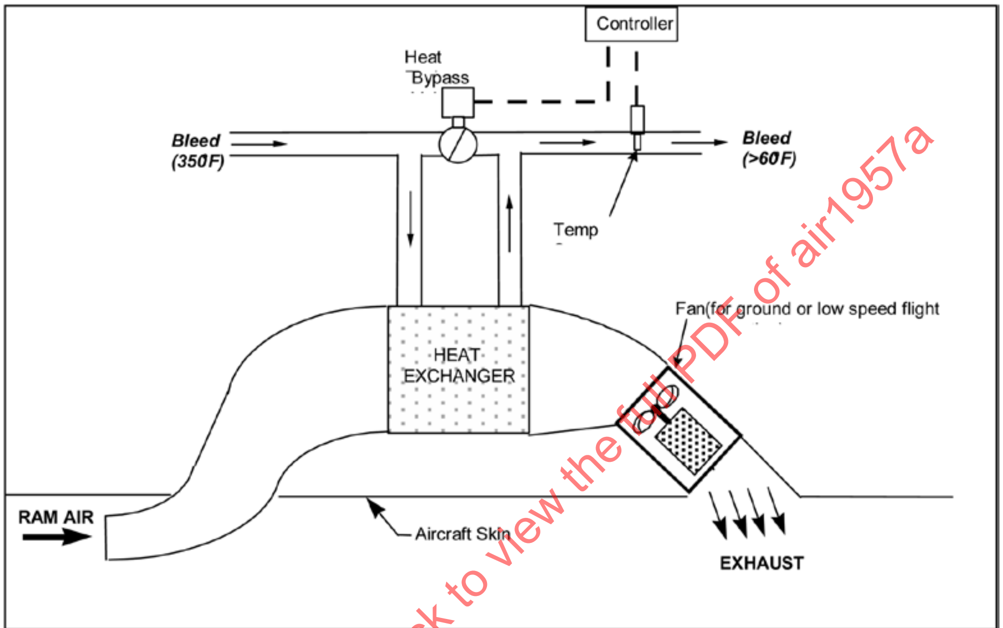

Figure 6 - Ram air heat sink with fan augmentation

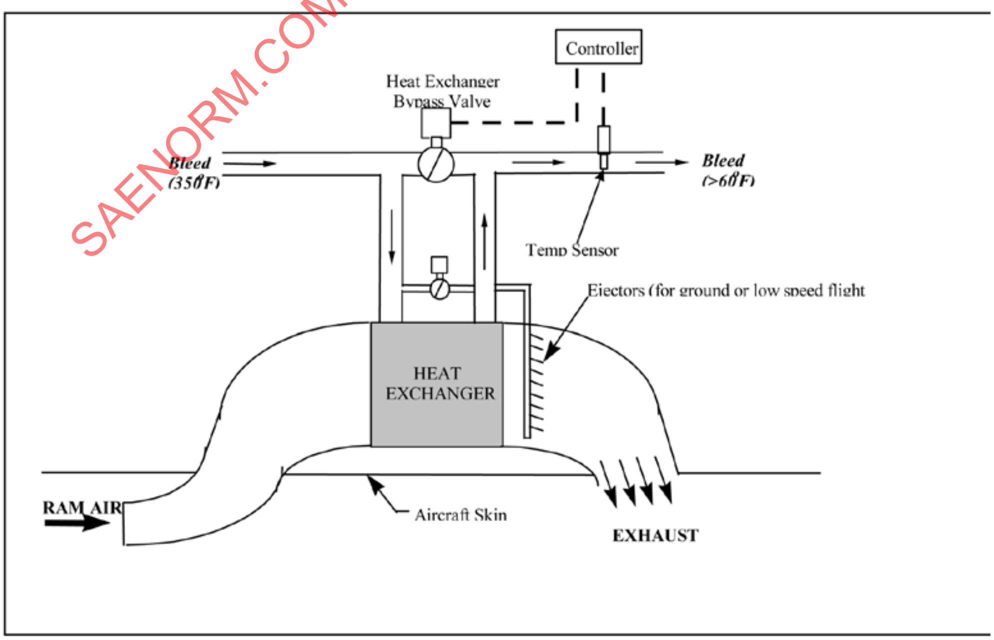

Figure 7 - Ram air heat sink with ejector augmentation

Generally a supersonic application does not differ from a subsonic regarding Heat Sink design aspects. However in general a flush inlet would not allow performance to be met at supersonic speeds. The design would need a scoop, which might be designed to capture air out in the free air stream vs inside the boundary layer.

7.4 Engine Fan Air Heat Sink

Fan air heat sink system design is generally similar to ram air system design. The principal differences are:

- Fan air pressure, and consequently flow, is available whenever the engine is running. Ram air flow depends on aircraft forward airspeed or, for ground operation and low speed flight, addition of a fan or ejector, as shown in Figure 6 and Figure 7.

- Fan air flow (and pressure) increases with engine power setting, while ram air flow (and pressure) depends on aircraft forward airspeed. The fan air pressure and flow availability with increased engine power is proportional to the increase in engine bleed air temperature substantially offsetting the benefit of higher cooling flow.

- Ram air systems that use a nose or non-flush inlet may require inlet ice protection or an alternate non-icing inlet. Fan air inlets do not require ice protection due to the normally hidden position from direct impingement and the additional heat of compression above the ram air temperature that occurs in the fan air duct.

7.4.1 Bleed Air Cooling using Fan Air Extraction

Fan air can be extracted from a port on the fan air duct and routed to a bleed air heat exchanger. Port location on the fan air duct should be chosen to provide the greatest fan air pressure recovery, minimum distance from the bleed air heat exchanger (to minimize fan air pressure drop) and to fit within the engine cowling. If space is not available in the engine cowling to install the bleed air heat exchange, a ducted installation as shown in Figure 8 or 9.

While the flush 90 degree port design shown in Figure 8 is most common, it recovers only the fan air static pressure. If space is available in the fan air duct wall, a recessed port, similar to ram air inlets, could be used to recover a portion of the fan air dynamic pressure.

Figure 8 illustrates a fan air extraction system that modulates bleed air through and bypasses the heat exchanger for bleed air temperature control. The disadvantages of this design are:

- Fan air is always being extracted regardless of heat exchanger cooling requirements. Even with efficient fan air duct and exhaust design, this results in a constant loss of engine thrust.

- The system in Figure 9 has several disadvantages when compared to the system in Figure 8. A constant flow through the heat exchanger results in a pressure drop on the bleed air side of the heat exchanger, even when bleed air cooling is not required. In addition, the system in Figure 9 has thermal losses due to conduction, convection, and ration heat loss, even when there is no fan air flow. These thermal losses may be unacceptable during low engine power or idle conditions when bleed air temperatures may not have sufficient heat, when used as the heating source, such as the trim air for the cabin.

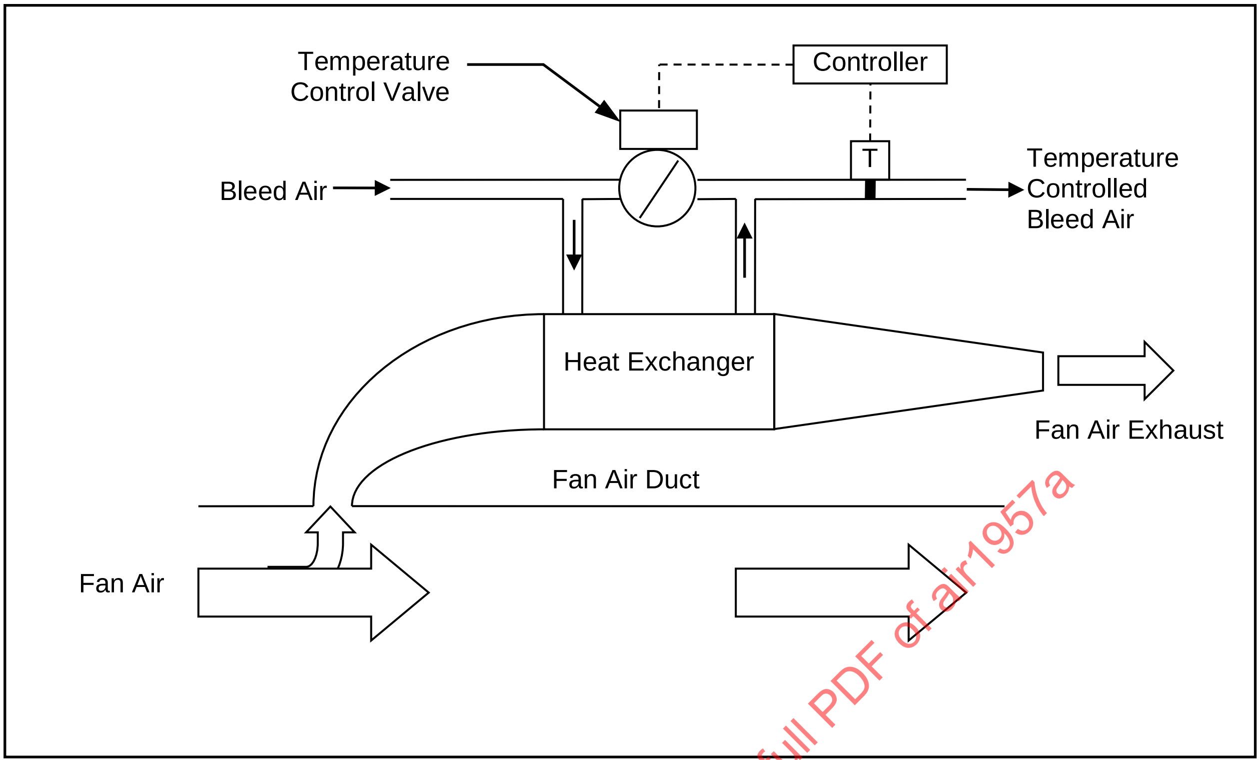

Figure 8 - Fan air extraction system with bleed air modulation temperature control

Figure 9 illustrates a fan air extraction system that modulates fan air flow for bleed air temperature control. This design eliminates the two disadvantages of the system shown in Figure 8; fan air flow can be completely shut off to eliminate thrust losses and bleed air cooling when cooling is not required.

Compared to Figure 8, this system has the disadvantages that the include a constant flow through the heat exchanger results in a always present larger pressure drop in the bleed side when bleed air cooling is not required. Since the system in Figure 8 can use a 3-way valve to completely bypass bleed air flow around the heat exchanger, the system in Figure 9 has and thermal losses due to conduction, convection and radiation heat loss from the heat exchanger even when there is no fan air flow, which may be unacceptable during low power engine idle conditions when bleed air is intended as a heating source used to heat the cabin.

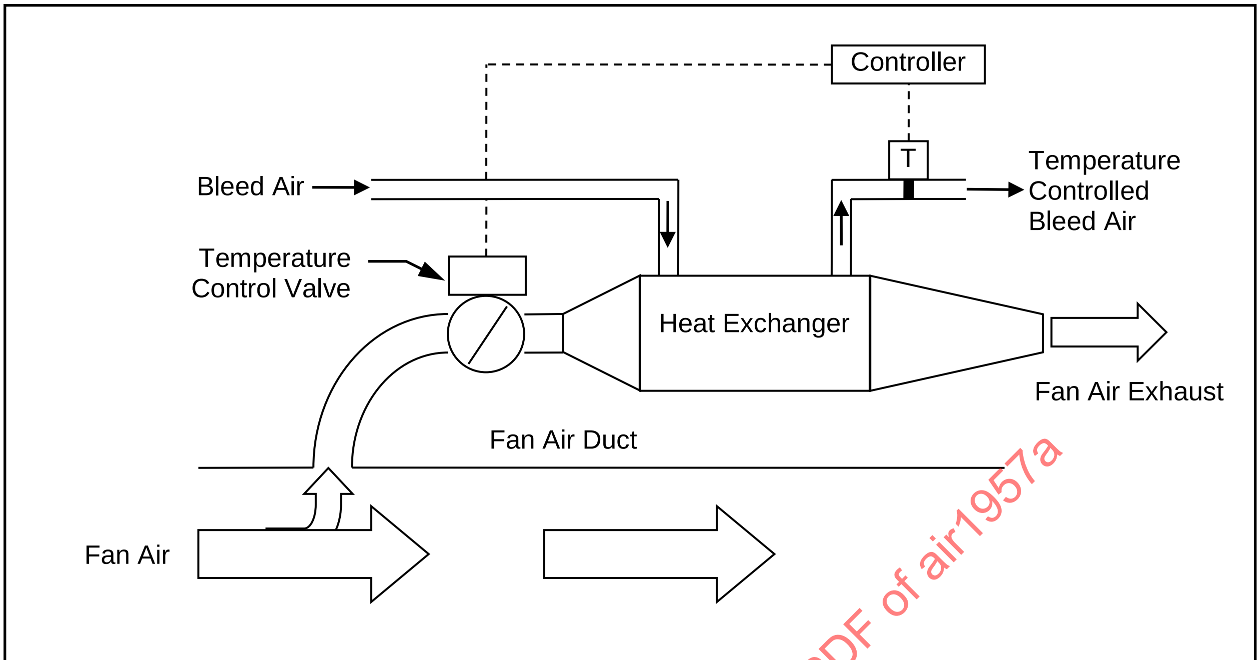

Figure 9 - Fan air extraction system with fan air modulation temperature control

7.4.2 Fan Duct Heat Exchangers

Bleed air heat exchangers may be installed directly in the fan air duct when there is limited space in the engine cowling. A typical system is shown in Figure 10.

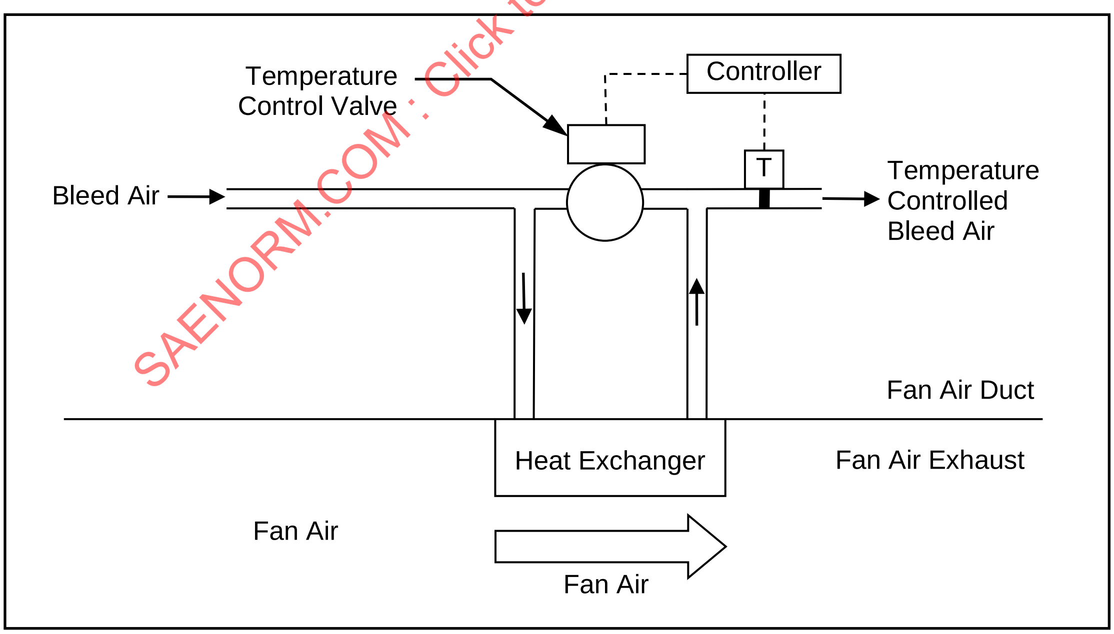

Figure 10 - Fan duct heat exchanger with bleed air modulation temperature control

The pressure available to force fan air through the heat exchanger is only the fan air dynamic pressure since the cooling air exhausts back into the fan air duct. The fan air dynamic pressure will generally be less than the fan air static pressure rise that is available to a fan air extraction system that exhausts overboard. The limited effect of the lower fan air dynamic pressure will be somewhat offset by the lack of pressure losses of the fan air extraction system required by the systems in Figures 8 and 9.

The fan duct heat exchanger installation shown in Figure 10 has the disadvantage of causing engine thrust losses due to the obstruction of the heat exchanger into the fan duct regardless of whether or not bleed air cooling is required. This can be reduced by recessing the heat exchanger partially into the fan air duct wall as shown in Figure 11, or completely as shown in Figure 12. The diverter door opens to allow fan air flow through only as necessary to cool the bleed air to the target control temperature. Fan duct heat exchangers can be used without the door mechanism.

A potential practical disadvantage of use of a diverter door for temperature control is that only a portion of the face of the heat exchanger will be exposed to the fan air when the door is partially open. This can result in large thermal gradients and stresses in the heat exchanger core, which would be applied repeatedly due to normal function of the temperature control system. This should be considered in heat exchanger design and qualification.

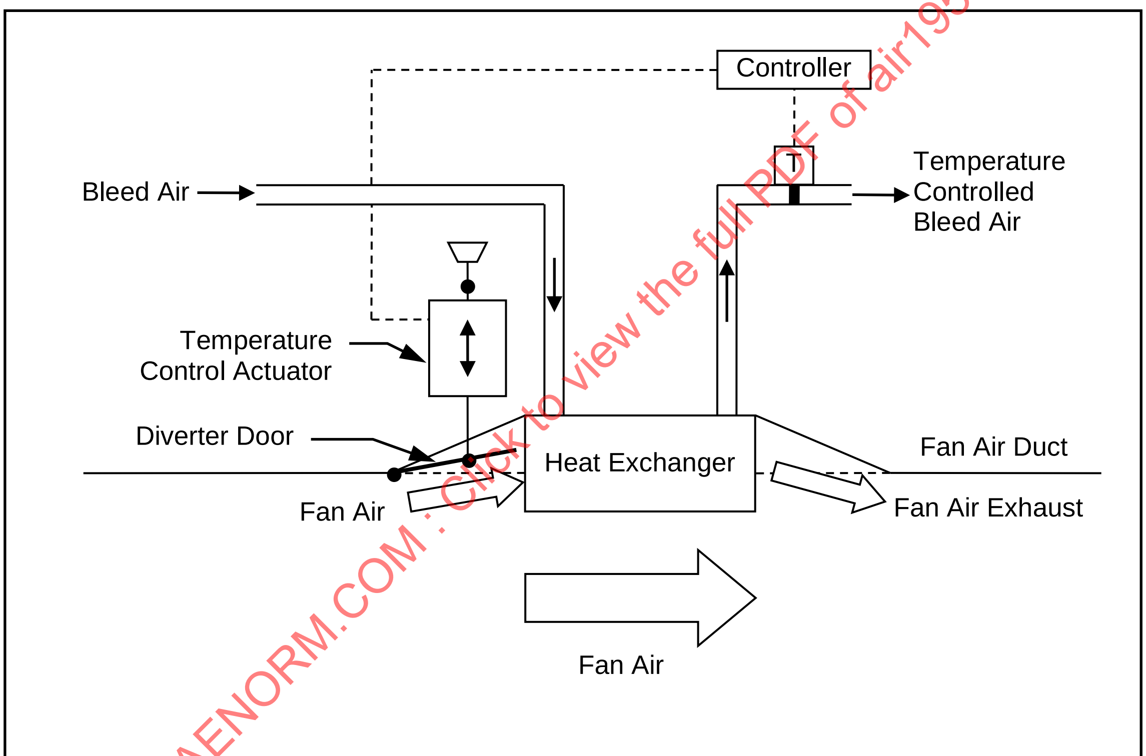

Figure 11 - Partially recessed fan duct heat exchanger with fan air modulation temperature control

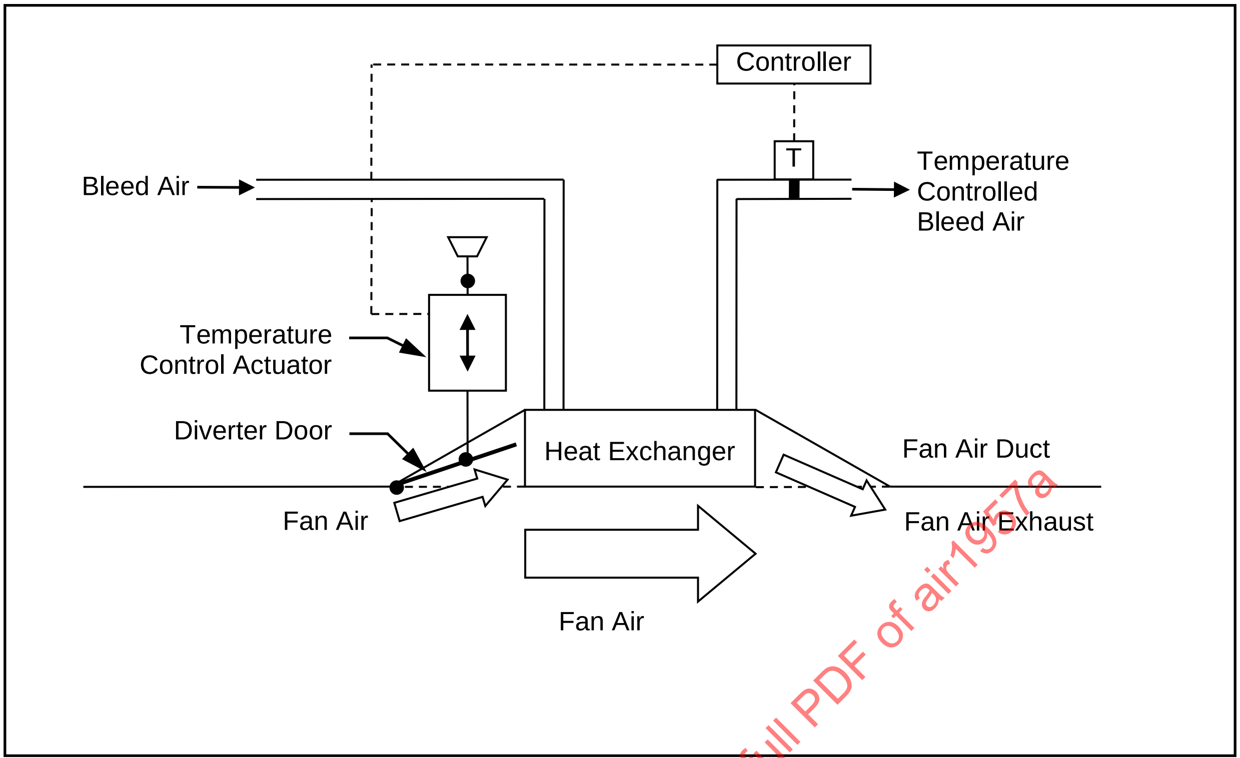

Figure 12 - Fully recessed fan duct heat exchanger with fan air modulation temperature control

Use of a partially or fully recessed fan duct heat exchanger installation will depend primarily on whether there is space available in the cowling and fan air duct for the heat exchanger, diverter door and actuator, inlet and outlet ramps, as well as the overall impact to the engine thrust capability.

7.5 Fuel Heat Sink

A limitation of a fuel heat sink is the maximum temperature that the fuel is permitted to reach prior to entering the engine. Engine fuel delivery temperature limits are based on engine use of the fuel to assure satisfactory engine performance. The limiting fuel temperature is determined by accounting for all heat transferred to fuel by the aircraft and engine heat loads to avoid reaching the coaking temperature of the fuel.

Currently fuel temperature limits at the engine interface range from 160 to 240 °F (71 to 116 °C). The maximum temperature limit of fuel supplied to engine combustors is 300 to 325 °F (149 to 163 °C), however additives and fuel from alternate sources such as Fischer-Tropsch fuels can increase the allowable temperature. Fuel, such as JP-8 +100, has been developed and provides increased fuel stability at temperatures ~100 F above the typical 325 °F limit. The difference in temperature reflects the heat input from engine lube oil, hydraulic oil, and engine fuel pumps.

The maximum allowable fuel temperature in the aircraft fuel tanks is another limitation associated with using fuel as a heat sink. In some designs, the fuel flow required by the engine is insufficient for cooling aircraft and engine heat without exceeding the engine temperature limit. To cool the heat load with fuel, while maintaining fuel temperatures below engine limits, flow rates are increased above engine requirements. Excess fuel flow is recirculated to the fuel tanks, adding heat to fuel in the tanks. The increase in bulk fuel temperature in the tanks must be determined throughout critical flights. All heat transferred to fuel, including heat from pumps and through tank walls, must be considered. End-of-flight fuel temperatures, in particular, must be evaluated, since less fuel remains to absorb heat added by recirculating fuel.

The temperature of fuel in a tank is a concern to prevent fuel from boiling. The boiling temperature is a function of the vapor pressure of the fuel and pressure of ullage in the tanks. Fuel tank pressurization is required to prevent boiling of high vapor pressure fuels, such as JP-4. Tanks are pressurized from 5 to 7 psi (34 to 48 kPa) above ambient in military aircraft. This allows maximum fuel temperatures up to 160 °F (71 °C) in the tanks. Low vapor pressure fuels, such as kerosene-based Jet A1 or JP-5, allow maximum fuel tank temperatures up to 300 °F (149 °C). A structure weight penalty is associated with pressurizing a fuel tank. Examples of fuel heat sink designs for several aircraft are found in Coons (1986) and AIR1812.

Another effect of high temperature on fuels is coking of hydrocarbon fuels under high temperature. This can result in plugging or deformation of spray patterns of fuel nozzles with solid particles.

The design of cooling system components that use fuel as a heat sink will be influenced by the fact that fuel is a flammable fluid. For example fuel heat exchangers may require special features such as barrier passages to prevent leakage of fuel into the cooling system fluid. Locations where components that utilize fuel are sited are to be designated as flammable fluid leakage zones. Equipment and wiring located in these zones have requirements levied on them to preclude ignition sources and to withstand internal explosions.

For airborne vehicles with On-Board Inert Gas Generation Systems (OBIGGS), the impact of heated inert gas supplied to the fuel tanks should be considered for any fuel tank thermal analysis. The inert gas supplied to the fuel tanks is controlled to a temperature in the order of 200 °F (typical material limitation within separators); the efficiency of typical OBIGGS air separators generally improves with increasing temperature. Fuel tank thermal analysis should consider the inert gas flow rates for the applicable flight phase. Inert gas flow rates can be on the order of 0.5 to 10 lb/min; the highest inert gas flow rates are during descent and the lowest flow rates are during cruise.

7.6 Expendable Heat Sink

Expendable heat sinks are normally liquids. Heat is absorbed by the latent heat of vaporization of the expendable liquid. Water is most commonly used because of the universal availability of the fluid and high thermal capacitance and has a high heat of vaporization. Ammonia and alcohol are also used. The boiling temperature of the liquid, at the pressure it will be used, is an important consideration when selecting the expendable liquid. Thermal properties of these three liquids, at several temperatures, are shown in Table 5.

Table 5 - Expendable heat sink capabilities of three liquids

Liquid	Temp (°F)	Temp (°C)	Latent Heat of Vapor (Btu/lbm)	Latent Heat of Vapor (kJ/kg)	Vapor Pressure (psia)	Vapor Pressure (kPa)	Density (lbm/ft^3)	Density (kg/m^3)
Ammonia	+20	-7	553	1,285	48.0	332	40	641
	+40	+4	535	1,243	73.3	505	39	625
	+60	+16	520	1,208	107.6	742	38	609
Methanol	+50	+10	507	1,178	1.0	7	50	801
	+100	+38	490	1,139	5.0	34	48	769
	+150	+66	472	1,097	15.0	103	47	753
	+200	+93	407	946	40.0	276	45	721
Water	+100	+38	1,037	2,410	1.0	7	62	993
	+150	+65	1,007	2,340	3.7	26	61	977
	+200	+93	978	2,273	11.5	79	60	961

An example of an expendable heat sink design is shown in Figure 13. Water, as an expendable heat sink, cools the transmitter and antenna modules of an ECM pod during periods of dash flight, as presented by Swain and Letton (1979). The flow schematic of Figure 13 indicates that ram air is used to cool pod heat loads during normal operation. The electronics heat loads are mounted on cold plate heat exchangers. Adjacent to the thin cold plates are water vaporizer heat exchanger surfaces. During high speed dash flight, when ram air is hot, the polyalphaolefin (PAO) coolant is diverted from the surface heat exchangers. The water absorbs the electronic heat load, via the liquid transport loop, and boils off at a temperature of 183 °F (84 °C) or higher. The water contains a molybdate inhibitor for corrosion protection.

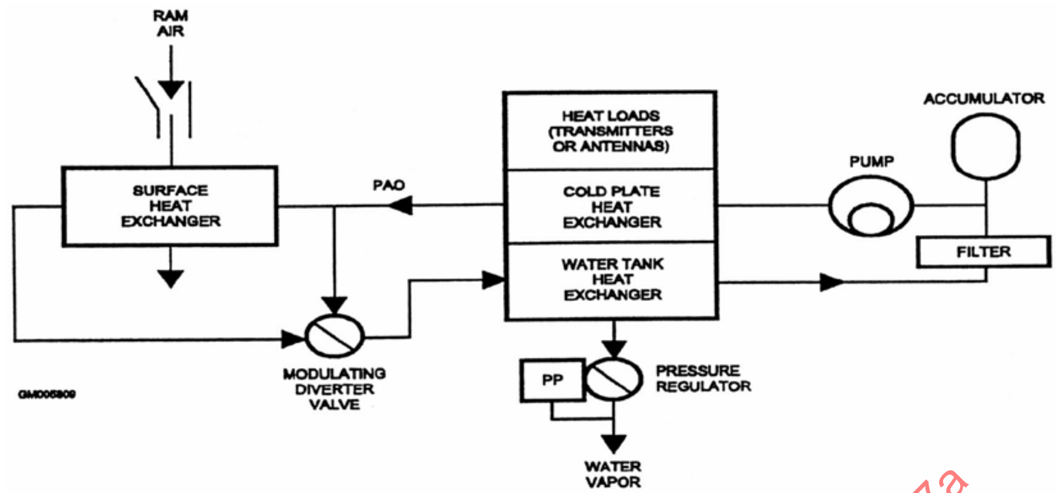

Figure 13 - Example of expendable water heat sink design

7.7 ECS Coolant Heat Sink

ECS air can be used in a regenerative fashion such that some of the cold air processed through the cooling turbine is supplied to a heat exchanger that cools incoming air. The use of ECS air for regenerative cooling is limited to a small percentage of the total airflow because ECS size is sensitive to this approach.

Heated ECS air may be used as a heat sink after it has cooled an initial heat load. It is used directly in the second heat load or indirectly via other fluid loops.

Avionic equipment in transport aircraft typically is cooled by cabin air. A common arrangement is shown in Figure 14. Cabin air is drawn into the compartment, through filters, by two parallel fans. Usually the fans are shut off when the cabin differential pressure reaches a predetermined amount. The cooling air flow is then achieved through cabin differential pressure. Air is distributed to the avionic units by branch ducting, and it is exhausted overboard through a flow control valve.

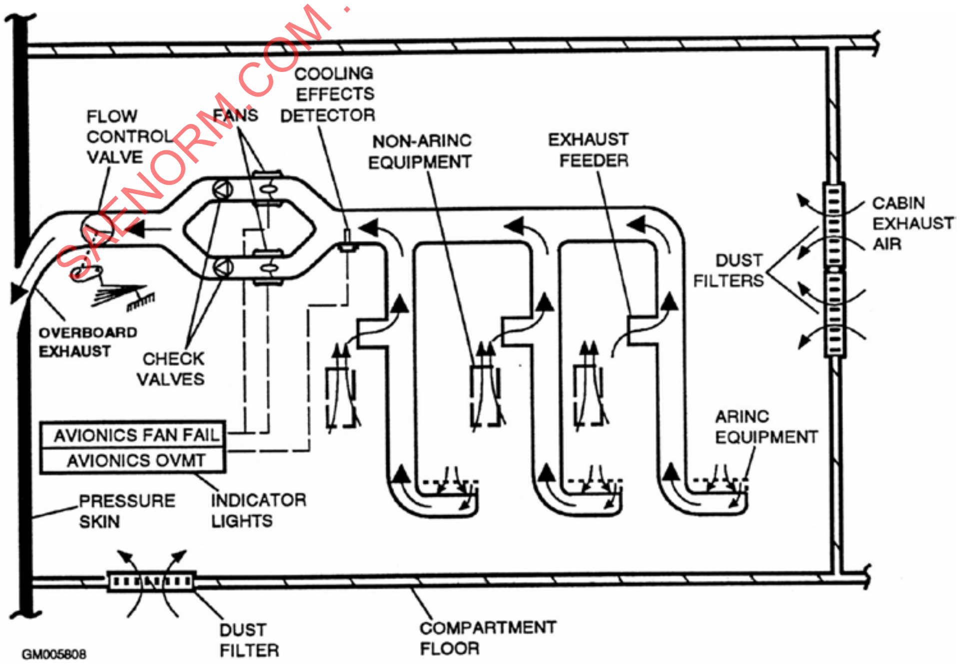

Figure 14 - Typical transport aircraft avionics cooling system