

(R) Environmental Control System Contamination

RATIONALE

AIR1539B has been reaffirmed to comply with the SAE five-year review policy.

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1. SCOPE

This publication will be limited to a discussion of liquid and particulate contaminants which enter the aircraft through the environmental control system (ECS). Gaseous contaminants such as ozone, fuel vapors, sulphates, etc., are not covered in this AIR. It will cover all contamination sources which interface with ECS, and the effects of this contamination on equipment. Methods of control will be limited to the equipment and interfacing ducting which normally falls within the responsibility of the ECS designer.

1.1 Purpose

The purpose of this Aerospace Information Report (AIR) is to categorize sources of ECS contaminants, define the effects of these contaminants on equipment, and outline design features that can be used to control contamination in aircraft systems.

2. 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, supercedes applicable laws and regulations unless a specific exemption has been obtained.

2.1 SAE Publications

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

AIR4766/1 Air Quality for Commercial Aircraft Cabin Particulate Contaminants

AIR4766/2 Airborne Chemicals in Aircraft Cabins

2.2 EASA Publications

Available from European Aviation Safety Agency, Postfach 10 12 53, D-50452 Koeln, Germany, Tel: +49-221-8999-000, www.easa.eu.int.

CS-E-690 Engine Bleed

2.3 U.S. Government Publications

Available from the Document Automation and Production Service (DAPS), Building 4/D, 700 Robbins Avenue, Philadelphia, PA 19111-5094, Tel: 215-697-6257, <http://assist.daps.dla.mil/quicksearch/>.

Statistical Abstract of the United States, 1967, Volume 1967-04. available on line from www.census.gov/prpd/www/abs/statab1951-1994.htm, pp180-183.

2.4 Other Applicable References

ASHRAE HANDBOOK, 1977 Fundamentals

Bishop, G., "Application of Self-Cleaning Air Cleaners to Aircraft and Vehicular Gas Turbines," Paper No. 68, Joint Gas Turbine Congress, Tokyo, 1977

Fairlie, D., Jacob, D., & Park, R.(2006). The impact of transpacific transport of mineral dust in the United States. Atmospheric Environment, Manuscript #ATMENV-D-06-00482R1, NASA Langley Research Center.

Lockheed-Georgia Company Report, 46-1327 C-130 Contamination Investigation

Parker, "Air Pollution at Heathrow Airport," London Dept. of Trade and Industry, Herts, England, Sept. 1970

Robins, C. S., Boeing Company, "737 Air Conditioning Engine Bleed Air Contamination." Nov. 1968

Robins, C.S., Boeing Company, 737 Engine Bleed Air Contamination Analysis for UAL, April 1969

Starrett, P.S., Lockheed-California Company, "Bleed Air Contamination Reduction Probes, EL/74-75-148," Sept. 1974

3. TYPES AND SOURCES OF CONTAMINATION

Three types of contamination are of concern to ECS design. The first of these is gaseous or vapor contamination. This may be generated within aircraft components or be present in the operating environment. This material can be introduced into the cabin through the ECS. This AIR does not discuss gaseous contaminants since AIR4766/2 provides an in depth discussion on gaseous contaminants from commercial aircraft cabins.

The second type is liquid contamination which can enter the ECS through an Auxiliary Power Unit (APU) or an engine. These liquids may occur as a result of leaking systems, parts failure, or improper servicing of systems.

The third type, and of most concern to the designer, is particulate contamination. This consists of sand and dust, metal and carbonaceous material which may be introduced into engines, APUs or ground carts as airborne particles or may be vacuumed off runways and ramps during takeoff and landing. This AIR does not discuss particulate contaminants since AIR4766/1 provides an in depth discussion on particulate contaminants for commercial aircraft cabins.

3.1 Sources of Liquid and Aerosol Contamination

3.1.1 Engine Lube Oil

Engine compressor bearings upstream of the bleed ports are the most likely sources of lube oil entry in the engine air system and thence into the bleed system contaminating the cabin/cockpit air conditioning systems. Although precautions are taken in the design of the bearings to preclude oil leakage into the compressor air passage, failure conditions can result in the introduction of oil into the airstream. At temperatures above 320 °C this oil may create irritating compounds. AIR4766/1 and AIR4766/2 discusses this in greater detail.

3.1.2 Compressor Section Compartment Cooling

Whenever possible all combustible fluid lines, fire extinguishing equipment and accessories are located in this area. If ram cooling or ventilating air is extracted from the engine inlet duct, then during ground operation a negative pressure is available at the engine inlet tending to induce reverse flow from the compartment into the engine airstream. If an oil or fuel leak occurs, or if a compressor wash is performed without following the published procedure, some of the detergent can remain in the engine and get into the ECS system. Under this condition the contaminants are introduced into engine air, thence into the bleed air supply to the cabin.

3.1.3 Operating Environment

Airport environments contain unburned or partially burned hydrocarbons. These contaminants, in the form of oily soot, enter the ECS through APUs, ground carts or engine bleed.

3.1.4 Other Liquid Contaminants

Any of the fluids used in the aircraft systems or as cleaning agents can be an ECS contaminant. These include lubricating oil, hydraulic fluids, fuel and even waste material. They usually enter the ECS through the APU inlet and may be airborne droplets or liquid runback along the skin. Aircraft de-icing can expose the APU or main engines to large quantities of glycol. This material will break down in the compressor and create irritating smoke which can quickly contaminate the entire ECS and cabin.

3.2 Particulate Contaminants

Dust particles in the atmosphere vary in size as well as quantity. Most particulates range in size from less than 1 micron up to about 100 microns. Permanent atmospheric impurities range up to 1 micron and except for outlet staining (in cabins) through a process known as the Coanda effect are not a serious problem.

Figure 1 (ASHRAE Handbook, 1977) shows the size distribution of particles which make up atmospheric dust. Figure 4 (Fairlie et al, 2006) shows the size distribution of particles with respect to altitude.

The region at the right of the weight curve in Figure 1 is the area of concern to aircraft ECS designers as well as the airline operators.

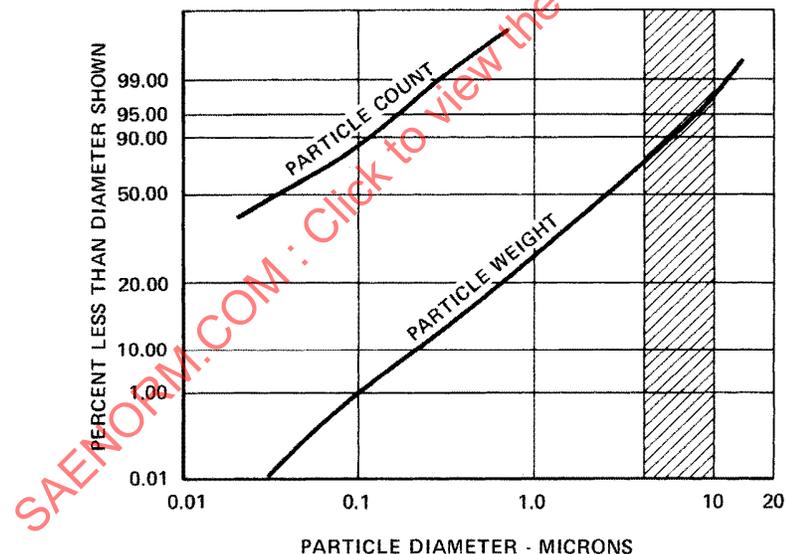


FIGURE 1 - PARTICLE SIZE DISTRIBUTION OF ATMOSPHERIC DUST

Figure 2 (Census, 1967) is based on U.S. Public Health Service samples of atmospheric dust in the USA and Rolls Royce data from an engine lab. This figure shows a wide range in the amount of dust contained in urban and rural atmosphere. In-flight particle sampling (Robins, 1968) showed that at 3000 feet the number of particles was less than 3% of that found during taxi. Runway dirt is characterized by a different particle size distribution than for atmospheric dust.

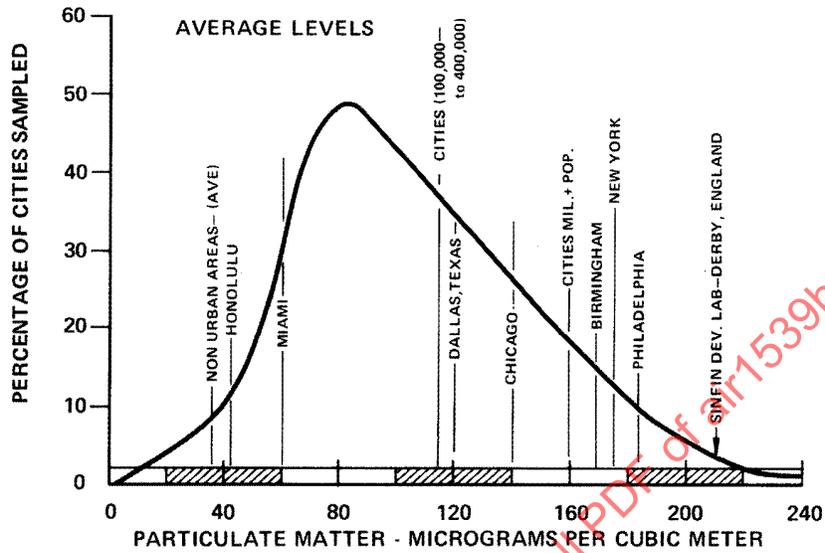


FIGURE 2 - DISTRIBUTION OF SUSPENDED PARTICULATE MATTER OF 234 CITIES SAMPLED, IN USA, 1965

Figure 3 shows an experimental particle count distribution by size. These data were developed as a result of C-130 aircraft operations (Lockheed Georgia Company Report).

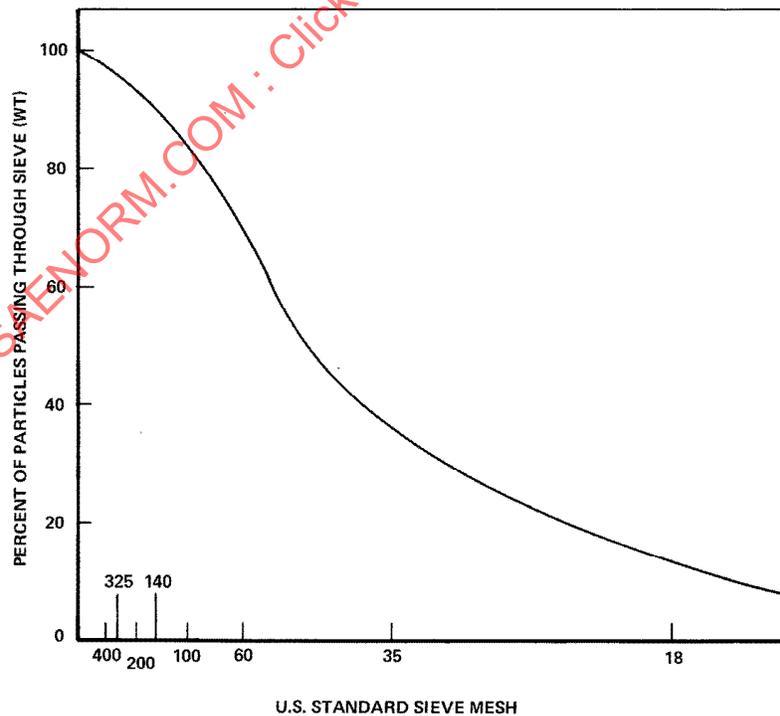


FIGURE 3 - RUNWAY DIRT PARTICLE SIZE DISTRIBUTION

Particulate contaminants may consist of a number of different materials depending on the operating environment, engine height above the runway, and inlet location in relation to the landing gear. Abrasive materials such as silica, metal chips, etc., are more likely to cause expansion turbine nozzle erosion whereas carbon particles and lint will block filters and orifices. Examples of the size and types of contaminants for a low wing mounted engine operating from two different airports in Washington are shown in Table 1 and 2 (Robins, 1969). An examination of contaminants found on a water separator bag from an in-service airplane with rear fuselage mounted engines operating from Kansas base shows carbonaceous material at 10%, siliceous material 35%, and the remainder metal chips.

TABLE 1 - SIZE OF PARTICLES CONTAMINATING VALVES AND WATER SEPARATORS

| Particle Size (microns) | <5 | 5-15 | 15-25 | 25-50 | 50-100 | >100 |
|-------------------------|-------|-------|-------|-------|--------|------|
| Percentage (Wt) | | | | | | |
| Valves | 20-40 | 30-40 | 20-30 | 5-15 | 3 | 2 |
| Water Separator Bags | 0 | 60 | 20 | 15 | 5 | <1 |

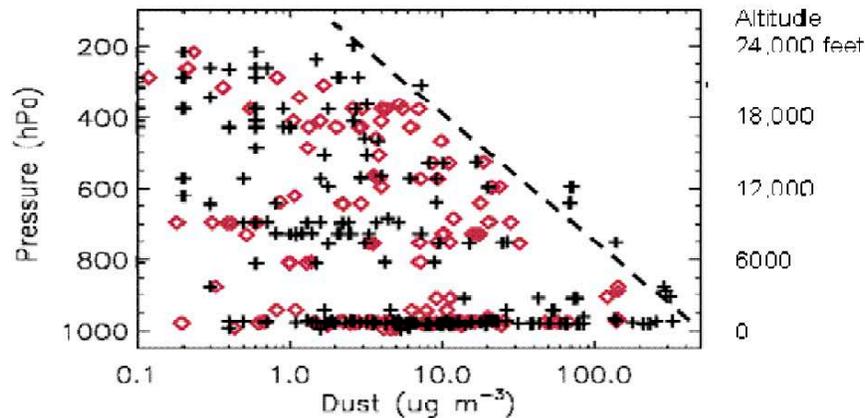
TABLE 2 - CONTAMINANT CONSTITUENTS FOUND IN COMPONENTS

| Material | Percentage by Weight | |
|-------------------|----------------------|------------------|
| | Valves | Water Separators |
| Carbonaceous | 40-60 | 60 |
| Copper | Trace | 1 |
| Aluminum, Steel | 1-2 | Trace |
| Siliceous | 30-56 | 40 |
| Plastic | Trace | 0 |
| Resinous | 1-3 | 0 |
| Fibers, Cellulose | 1 | Trace |

Particulates can enter the ECS through the engine, the APU, through ground carts, and where auxiliary venting is provided, through the ram air inlets. All sources must be considered in developing contamination controls.

3.2.1 Engine Bleed

This source ingests particulates during all ground operations, low altitude climb and descent. From 25% to 30% of the total will be ingested during the takeoff run and 10% to 50% during approach and thrust reversal for a wing engine mounted close to the ground. The remainder will be ingested during ramp and taxi operations. For aft fuselage mounted engines by far the largest amount of dirt enters during reverse thrust operation. See Figure 4 for the relationship between particle size and altitude in one study.



Altitude distribution of mineral dust offshore from East Asia in spring 2001.

FIGURE 4 - PARTICLE SIZE DISTRIBUTION OF ATMOSPHERIC DUST WITH RESPECT TO ALTITUDE

The importance of engine bleed port design should be noted. In order to be in compliance with CS E-690 engine compressors should not cause particulate matter to be concentrated in air supplied to the bleed air system. Turbofan engines largely avoid this problem because much of the centrifuging occurs prior to entry of the air into the compressor, routing heavy particles into the fan duct. However, in turbojets or very low bypass ratio turbofans if the extraction air is bled at the periphery of the compressor housing (OD bleed) without inertial separation designed into the takeoff, the particulate concentration is much higher than the average concentration across the engine air inlet. Engines with provisions for bleed air extraction from the inside diameter (ID) of the compressor airflow passage (ID bleed) have shown much less bleed air contamination than air extracted from an improperly designed outside diameter (OD) port. However, ID bleed configurations can possess a higher risk of oil contamination from the lubrication system and should be sufficiently partitioned to minimize the likelihood of this type of contamination.

Contamination control through bleed port design becomes even more important as engine size and thrust increase. Engines in the 20,000 kg thrust range have total inlet flows of up to 700 kg/s. This flow creates a runway vacuuming action for under wing engines during the takeoff run unless design features are incorporated to break up the attached vortex. With the vortex action from runway to engine inlet, the portion of contamination attributed to this portion of the flight may be quite high.

3.2.2 APU and Ground Carts

Because these sources always operate in the contaminated airport environment, they may transmit a high percentage of the contamination to the system. Figure 5 shows the potential high percentage of contamination due to ground operation with a ground cart or an APU having an inlet close to the ground. This is shown as a function of the ratio of hours of APU and ground operation to total flight hours. These predictions are based on aircraft operations from Boeing Field and Moses Lake (Robins, 1969) and the relative contaminant populations for operations (Parker, 1979; Robins, 1968). Measurements made on a rear fuselage mounted airplane in airline service showed the contribution made by the APU to be small compared to that entering the ECS during main engine reverse thrust application. If APUs and ground carts extract bleed air from the compressor stage, the bleed ports should be designed to remove particulates as in the main engines.

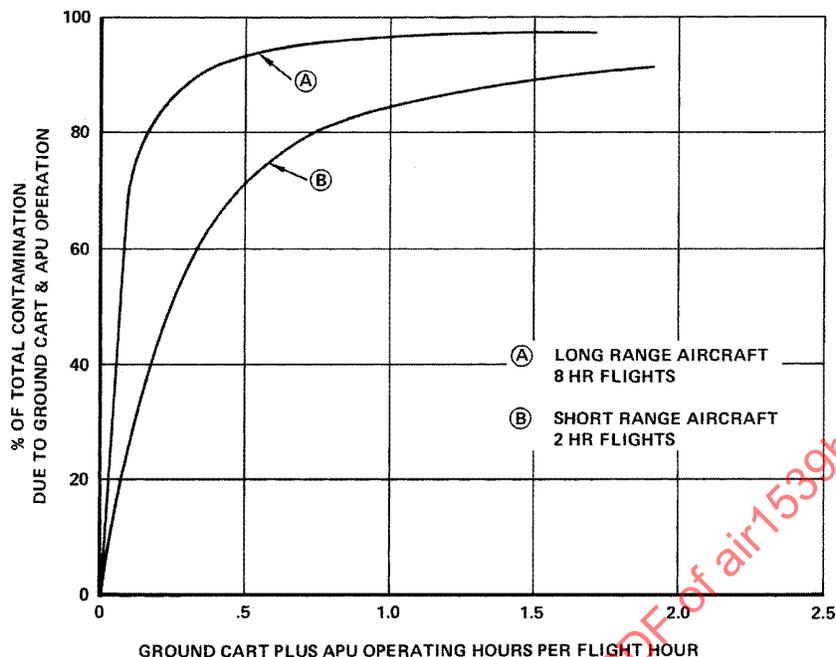


FIGURE 5 - SOURCES OF CONTAMINATION

3.2.3 Cabin Contaminants

Fibrous materials in the form of lint emanates from carpeting, seat materials and passenger luggage and clothing. There is no way to eliminate the sources of lint in the cabin and it poses a serious problem to cabin and avionics equipment.

Tobacco tars are also contaminants which cannot be controlled at the source. Tars deposit onto cold surfaces and form a sticky residue, often combining with lint and particulates. The prohibition on smoking has greatly reduced contamination from tobacco tar deposits.

4. EFFECTS OF CONTAMINATION ON AIRCRAFT SYSTEMS

Atmospheric dust ingested by the engines, APUs, and high pressure ground carts is the primary aircraft system source of contamination. It is possible that some particulates may be generated in the engines, particularly during initial run-ins; however, these are not considered serious contributors to overall contamination. There are, however, some internally generated contaminants, including carbon and oil vapors, that do affect components. Oil can be important in moderate quantities as a binder to solid particulate contaminants. These deposits can collect on filters and seals, in Air Cycle Machine (ACM) bearings, and in heat exchangers and can cause pneumatic component malfunction more rapidly than atmospheric contaminants.

The effect on equipment of particulates from pneumatic bleed air may be evident in any one or all of several different ways. The presence of contaminants can have a marked effect in: (1) degrading system performance, (2) requiring more frequent in-service maintenance, (3) increasing component removal rates, and (4) increasing shop overhaul rates.

4.1 Effects of Contamination on Equipment Performance and Life

Any equipment which is exposed to bleed air contaminants from the main engines or auxiliary engines should be evaluated as regards susceptibility to reduction in performance or life.

Performance degradation occurs when accumulations of contaminants or wear of components reduce the effectiveness of heat exchangers, turbomachinery, pneumatic or fluidic controls and water separators. Some of the impacts are readily identifiable while others may be quite subtle. The latter increases the complexity of fault isolation procedures and are often difficult to prove.

Performance degradation accounts for increased cost to the user, even though it is not as visible as specific hardware failures, because it results in increased maintenance and overhaul costs. System installation factors can have a profound influence on the exposure of components to harmful contamination.

4.1.1 Pneumatic Valves and Regulators

In general regulating devices are affected by the accumulation of dirt in critical orifices, in seal rings, in actuators, and in small passages. The effects of this dirt are a shift in calibration, increases in leakage, sticky operation, and a failure to operate at all.

Critical pneumatic control circuits should include dirt removal devices to minimize the effects of contamination.

The choice between using relieving or non-relieving filters or inertial dirt separation feature can be made only after analyzing the effects of a plugged filter on system and aircraft performance.

4.1.2 Air Cycle Cooling Turbines

Air cycle cooling turbines are one of the major components entailing increased costs in environmental systems as a result of contamination present in bleed air. Particulate contaminants are extremely harmful, especially siliceous materials which constitute the main contaminant in bleed air.

The principal problem resulting from operating of cooling turbines with dirt contaminated bleed air is erosion damage to the turbine nozzle. Secondary problems are damage to the turbine wheel and bearing failures due to dirt ingested into the oil sump. Particulate contaminants larger than approximately 10 microns in size, due to the mass of these particles, do not follow the airflow path at the nozzle exit but instead strike the turbine wheel blade tips. The stagnation of particle movement between the turbine wheel inlet and the nozzle outlet generate wear or erosion of both turbine blades and nozzle outlets. When the particles are broken down to approximately 5 microns in size or smaller, they then pass through the turbine wheel and into the water separator and cabin air distribution system. Extensive laboratory test experience and field experience has demonstrated that the turbine wheel damage due to erosion is much less severe than the damage to the turbine nozzle.

In the first stages of nozzle erosion there is very little loss of performance. Performance begins to seriously degrade when the throat area is enlarged as the wear progresses radially. Airflow through the turbine increases; however, total cooling decreases as turbine efficiency is reduced.

The rate of wear is a function of nozzle material, surface finish characteristics as well as other variables, most particularly the airline route structure, the design of bleed ports, and particulate infiltration rate.

The turbine wheel erodes from the direct impingement of contaminated air from the nozzle. Erosion continues until the blade tip is worn to a sharp edge. Up to this point no performance degradation occurs. With further erosion, the blade becomes shorter and as the clearance between the blade and the nozzle ring increases, efficiency starts to drop off. Figure 6 shows how cabin temperature and airflow typically increase with air cycle machine nozzle erosion.

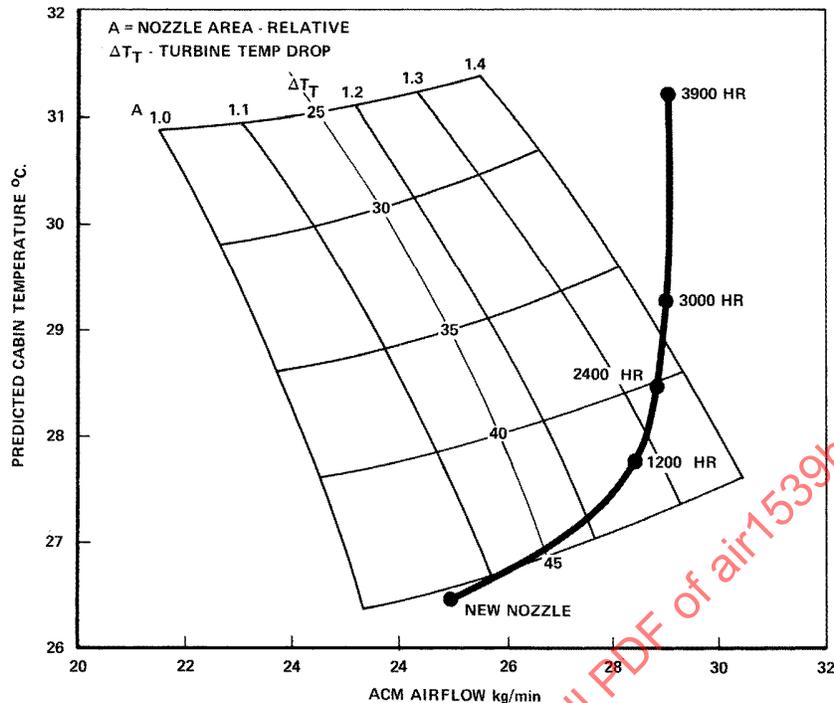


FIGURE 6 - EFFECT OF BLEED AIR AND RAM AIR TURBINE NOZZLE WEAR ON CABIN TEMPERATURE OF COMMERCIAL TRANSPORT AIRPLANES

Where oil lubricated bearings are used, contamination of the oil can occur due to bleed air and/or ram air contamination. Airline operators have reported higher bearing failure rates with contaminated bleed air than with the same systems incorporating air cleaners. While accurate records are not available, samples of oil from cooling turbines with differing operational times have all indicated a high grit content. The grit migrates through the shaft and wheel seals into the oil with obvious consequences. This, in combination with unbalance caused by erosion, accelerates wear-out of the bearings.

Air bearings may be subject to contamination damage from particulates and condensed fluids in bleed air used to pressurize or cool the bearings.

4.1.3 Bleed Air Heat Exchangers

Bleed air contamination has presented a problem in many aircraft environmental control system heat exchanger installations. The result is degradation of performance due to increase in pressure drop in external or internal passages which reduces ram flow and turbine pressure ratio. As contamination builds up on heat transfer surfaces, resistance to heat flow increases further reducing performance. Severe blockage of the ram air passages can cause the air cycle machine to shut down due to excessive temperatures.

Most compact designs are plate fin. The fins may be either straight (with or without offset), wavy, or ruffled. Susceptibility to dirt blockage depends on fin spacing and type of arrangement. For the same fin pitch, the contamination of a plain fin is less severe than for a wavy, which is less severe than a ruffled fin. Bleed air side fins may be as dense as 7 to 8 fins/cm. Combined with the offset, the effective flow passage depth is thus less than 0.051 cm average with minimum metal thickness, which is comparable to the smallest diameter orifices normally used in pneumatic systems.

Particles have a greater opportunity to drop out of the flow path if the cross sectional area of the duct is greater prior to the heat exchanger, resulting in a drop in particle velocity.

Heat exchanger cooling air inlet location affects the contamination of the units. If the airplane operating environment includes large quantities of dirt and debris on runway and taxi areas, the heat exchanger ram air inlets should be located as far away as possible from contaminated areas such as the landing gear and thrust reversers. If this is not possible, an alternate inlet designed to separate particulates may be needed for ground operation. A procedural approach of closing air inlets to the cold side of the heat exchanger may also be utilized during takeoffs and landings by using a closing device (ram air door) in front of the cold side of the heat exchanger. Contamination could also affect the hot side of the heat exchanger. In this case a dust separator upstream of the the cooling pack could reduce the heat exchanger contamination.

4.1.4 Avionics Equipment

Suction cooled avionic equipment is subject to contamination from lint, other fibrous materials, tobacco tars, and airborne particulates. Contamination will coat heat transfer surfaces, block internal cooling passages, disrupt cooling flow distribution, and reduce overall cooling flow. Like heat exchangers, avionics are affected by particulate contaminants which can coat surfaces and reduce heat transfer, thereby reducing component reliability. The buildup of contaminants depends on the total through-flow as well as the types of contaminants in the compartment air.

5. CONTROL OF CONTAMINANTS

The obvious solution to contamination problems is to prevent contamination at the source. This means that bleed ports must be designed to separate atmospheric dirt before it enters the ECS. The current state of the art indicates that about 60% of the atmospheric contaminants will be removed by good OD port design and 95% with good ID port design.

5.1 Bleed Air Cleaners

In general, bleed air cleaners are highly efficient, removing more than 90% by weight of the particles entering them. The efficiency of these cleaners increases with particle size, so that their efficiency in reducing ACM nozzle erosion is greater than 90%.

Most cleaners designed for aircraft applications depend on centrifuging dirt particles to the outer periphery where the heavily contaminated air is purged with scavenge flow. The cleaner can be installed with continuous scavenge flow, or can be fitted with shutoff valves that allow scavenge flow only during ground and low altitude operation. Depending on cleaner design, scavenge flow of from zero to as high as 6% through-flow is required to achieve dirt separation efficiency of 90 to 95%.

Bleed air cleaners affect system performance two ways. First, there is the loss of scavenge flow. The scavenge flow may be reduced to 0.2% to 0.5% of through-flow for cleaner designs which utilize recirculation. Designs are available to collect contaminants in a container, thus reducing bleed loss to zero. Second, cleaners also have a pressure drop which will affect ACM performance. The combination of scavenge flow loss and pressure drop can increase cabin temperature at design point conditions about 1°C.

Typically cleaners sized for flows of up to 50 kg/min at a pressure loss of about 3.0 kPa will be about 50 cm long, have a body diameter of 20 cm and will weigh about 5.4 kg.

5.1.1 Cleaner Installation

Cleaner installation should consider all the contaminant sources and the equipment to be protected. Both APUs and ground carts are sources of contamination and cleaners must be located to remove contamination from these sources as well as the main engines. Although cleaners will protect all components to some degree, their greatest value is in protecting equipment such as control valves, ACMs, heat exchangers and water separators.