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ENVIRONMENTAL CONTROL SYSTEM CONTAMINATION

1.0 PURPOSE

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

2.0 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 responsiblity of the ECS designer.

3.0 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.

The second type is liquid contamination which can enter the ECS through an APU or an engine. These liquids usually occur as a result of leaking systems or careless 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, APU's or ground carts as airborne particles or may be vacuumed off runways and ramps during takeoff and landing.

3.1 SOURCES OF VAPOROUS CONTAMINATION

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 breaks down into irritating and toxic compounds.

Accessories

Accessories located in the engine inlet air stream and driven by the main engine shaft have resulted in the leakage of various fluids into the airstream entering the compressor.

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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 fire extinguisher fluid is discharged under this condition, the contaminants are introduced into engine air thence into the bleed air supply to the cabin.

Air Cycle Machine

Oil from sump or pre-lubed bearings can enter in the event of a bearing or seal failure. The quantity of oil is limited and normally creates a nuisance rather than an operating or maintenance problem. However, there have been instances of emergency evacuation because of smoke following an air cycle machine seal failure.

Operating Environment

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

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) are not a serious problem.

Figure 1, which is taken from Reference 1, shows the size distribution of particles which make up atmospheric dust.

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 2 (Reference 2) 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 (Reference 6) showed that at 3000 ft. 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 3 shows an experimental particle count distribution by size. These data were developed as a result of C-130 aircraft operations (Reference 3).

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 materiaals 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 I and II (Reference 4). 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 I. 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 II. CONTAMINANT CONSTITUENTS FOUND IN COMPONENTS

	PERCENTAGE BY WEIGHT	
MATERIAL	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 percent 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.

The importance of engine bleed port design should be noted. Engine compressors concentrate particulate matter as a result of centrifugal action in the engine compressor section. 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 of the compressor airflow passage (ID bleed) have shown much less bleed air contamination than air extracted from an improperly designed O.D. 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/sec. 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 atmosphere, they may contribute a high percentage of the contamination to the system. Figure 4 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 (Reference 4) and the relative contaminant populations for operations (Reference 5 and 6). 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 system during main engine reverse thrust application.

If APU's and ground carts extract bleed air from the compressor stage, the bleed ports should be designed to remove particulates as in the main engines.

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.

4.0 EFFECTS OF CONTAMINATION ON AIRCRAFT SYSTEMS

Atmospheric dust ingested by the engines, APU's, 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 bearings, and in heat exchangers and can cause pneumatic component malfunction just as rapidly as the atmospheric dusts.

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 efficiency 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 increase the complexity of fault isolation procedures and are often difficult to troubleshoot. In both ways increased cost to the user is the result; with the overall system effect of combined component deficiencies being intangible as compared to specific hardware failures and 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 and are thrown outward against the nozzle. This process is repeated until finally the particles are broken down to approximately 5 microns in size or smaller and 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 and surface characteristics as well as other variables, most particularly the airline route structure and the design of bleed ports.

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 5 shows how cabin temperature and airflow typically increase with air cycle machine nozzle erosion.

Where oil lubricated bearings are used, contamination of the oil can occur due to bleed air 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.

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 .051 cm. average with minimum metal thickness, which is comparable to the smallest diameter orifices normally used in pneumatic systems.

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.

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 block internal cooling passages, disrupt cooling flow distribution, and reduce overall cooling flow. This causes equipment to operate hotter which reduces reliability and eventually can cause complete failure. The buildup of contaminants depends on the total through-flow as well as the contamination population in the compartment air.

5.0 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 O.D. port design and 95% with good I.D. 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% of 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. (1500 SCFM) at a pressure loss of about 3.0 kPa. (0.44 PSI) 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 must consider all the contaminant sources and the equipment to be protected. Both APU's 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, ACM's, heat exchangers and water separators.

5.2 FILTERS - ECS AND AVIONIC EQUIPMENT

Total flow filters are not a practical means of protecting ECS components. To be effective such filters must remove fine particles. Filters designed for high efficiency in the 5 - 10 micrometer particle range have high pressure drops and plug rapidly. This is a high maintenance cost, and can cause equipment failure if filters are blocked. An exception to this is in the use of filters to protect critical avionics equipment. Rack filters designed to trap lint are practical if carefully installed. Such filters should have low face velocities, large dirt holding capacity and be easily removed for cleaning or replacement.

5.3 COMPONENT DESIGN

Pneumatic components should be designed to accommodate contaminants to the greatest degree possible.

This can be done by reducing servo through-flow, maintaining large control orifices, using diaphragm actuators instead of expanding seal rings, and protecting critical pneumatic circuits with adequate dirt removal features. Actuator shafts must be sealed using preformed packing or other shaft seals. In general, bearings should be protected with dust caps and good seals to reduce leakage. Suitable materials should be used when high velocity air is involved, such as a nearly-closed butterfly or poppet.

Regulating devices are very vulnerable to contamination since they usually contain small passages, orifices, valves and capillaries. Fluidic circuits require special care when using bleed air for power since they inherently have very small flow passages and require airflow to operate, as compared to certain other pneumatic devices which can operate on air pressure without flow.

High velocity jets containing siliceous particles such as the primary of a bleed-powered jet pump must not impinge on ducts or components at high velocity. This can cause serious erosion.

5.3.1 Pressure Pickups

Some recent testing has shown that a simple reverse facing stream static probe as shown by Figure 6, can be used which will greatly reduce contaminant pickup (Reference 7). Although there is a loss of pressure equal to about one dynamic head with a reverse facing probe, the error may be acceptable in many applications.

The performance of this type pickup is summarized in Table III.

TABLE III. REVERSE STREAM PROBE PERFORMANCE

AIR VELOCITY m/sec	DIRT PICKUP (1)		STATIC PRESSURE ERROR (2)
	0-15μ	>15μ	kPa
15	25%	2%	- 0.15
30	20%	0%	- 0.52
60	6%	0%	- 1.89

(1) Measured as % of dirt collected through static port.

(2) Compared to a flush static port.

The dimensions of the stream probe are shown in Figure 6.

5.3.2 Erosion Resistant Turbine Nozzle Materials

These have included dimonizing (an electrode deposited tungsten carbide coating), hardened 440 stainless steel insert rings in the nozzle exit area, tungsten carbide nozzle insert rings, polyurethane rubber nozzle inserts, ceramic nozzle insert rings and others. All of these nozzle designs show some improvement in operational life with varying increased cost of manufacture. The greatest improvement is shown by the tungsten carbide insert ring. The polyurethane nozzle material shows an improvement in life; however, the resilient action of the material results in greatly accelerated turbine wheel erosion. A patent has been granted for a feature which purges dirty air from the nozzle ring at the interface with the wheel. In this way dirt is removed with a minimum of erosion.

5.4 ENGINE INLET FILTERS

Where turbine engine aircraft, particularly helicopters, operate in severely contaminated environments (fields, unprepared sites, etc.), erosion and contamination of engine compressors and turbines is so severe that installation of a cleaner in the engine inlet should be considered. Self cleaning bleed powered cleaners have been developed for this application that reduce contamination 90% and have acceptable pressure loss.

These cleaners are usually inertial type which require no regular maintenance. Barrier filters may also be used but have been found inadequate in many applications because of rapid clogging, increasing pressure and power loss, and logistics problems in remote areas. Engine inlet inertial air cleaners used on regenerative gas turbines typically impose an engine horsepower loss of about 2% (Reference 8).

5.5 PROTECTION AGAINST LIQUID CONTAMINANTS

Unless trade studies indicate otherwise, APU inlets should not be located on the bottom of the fuselage where there is maximum exposure to runway debris, fluid leakage, and runback. The APU engine inlet and the APU load compressor inlet, when applicable, should be located high on the fuselage or fin. However, at these locations snow and rain entry must be evaluated.

Avoid exposing APU inlets to contamination from overboard drain masts, waste tank vents, and fuselage drains.

APU inlets can be protected against liquid runback by inlet chevrons or surrounding deflectors that divert the flow of liquids around the inlet.

Deflectors must be designed for flight and static operation and must be located so that any liquids which drip off them are not ingested as airborne droplets.

6.0 REFERENCES

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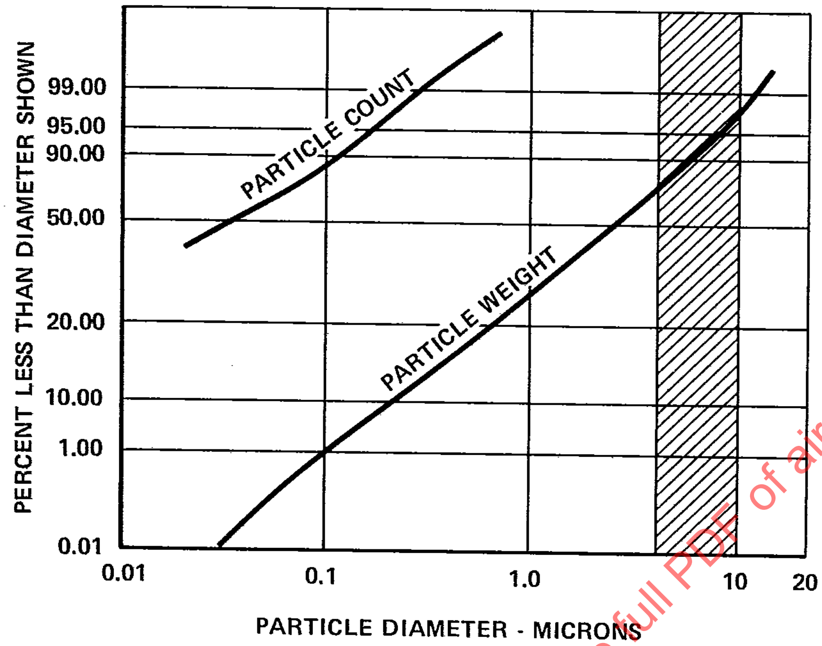

Figure 1. Particle Size Distribution of Atmospheric Dust

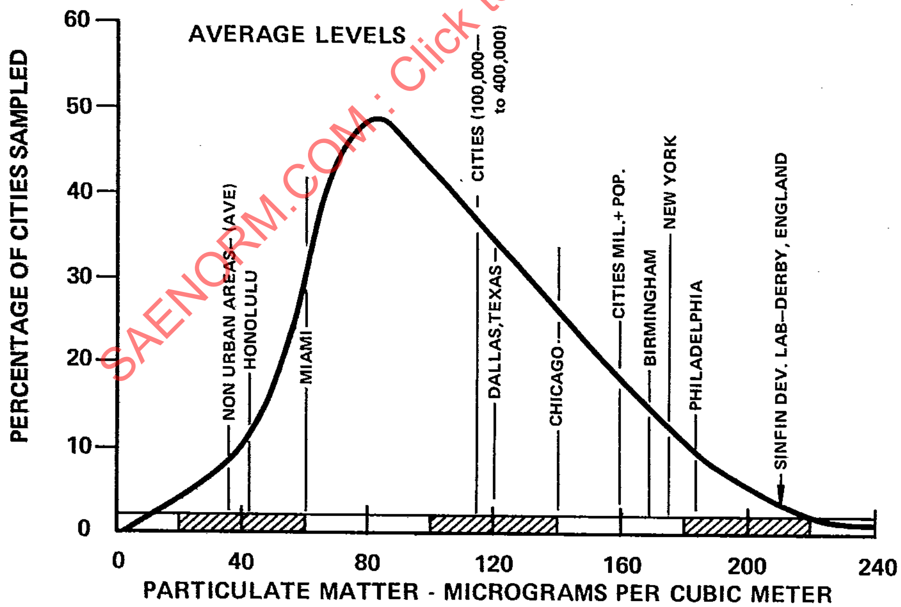

Figure 2. Distribution of Suspended Particulate Matter of 234 Cities Sampled, in USA, 1965

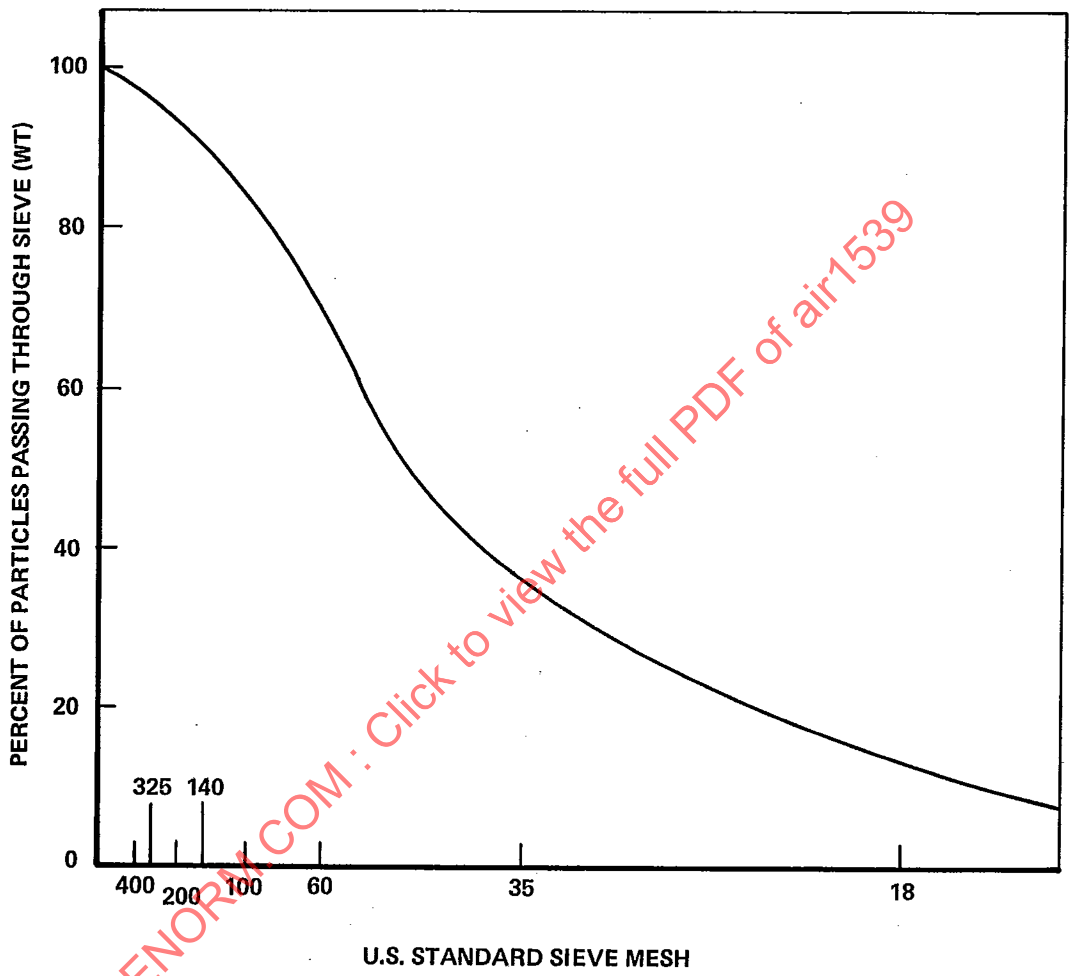

Figure 3. Runway Dirt Particle Size Distribution