ICAS PAPER
No. 72 – 02

SAND EROSION OF GAS TURBINES

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The Eighth Congress of the International Council of the Aeronautical Sciences

INTERNATIONAAL CONGRESCENTRUM RAI-AMSTERDAM, THE NETHERLANDS
AUGUST 28 TO SEPTEMBER 2, 1972

Price: 3. Dfl.

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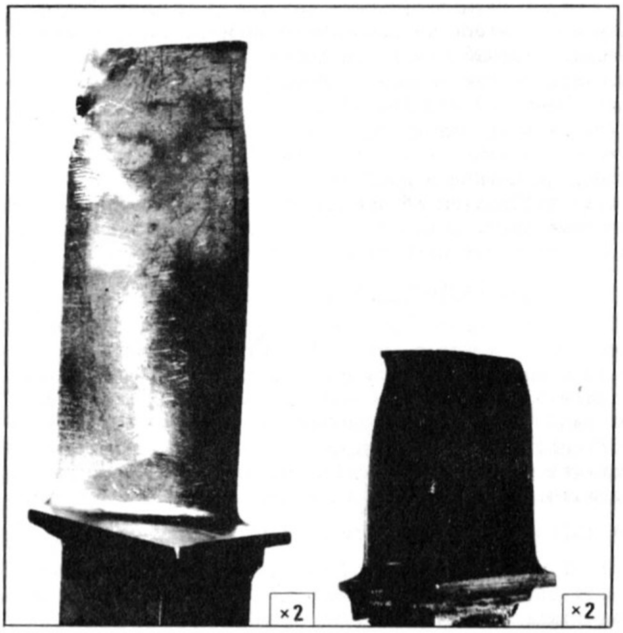
Abstract

Operation of gas turbines in dusty environments can involve the creation of dust clouds leading to ingestion of abrasive material. Over a period of time, relatively low dust concentrations can cause severe erosion damage to the compressor blading. In civil aircraft, this results in premature removal of blading leading to increased operational costs. In helicopters, usually involving more damaging environments, the erosion can occur more rapidly and lead to engine failures in relatively short times.

The relationships between erosion and the impact conditions are considered and the equations governing the behaviour are given. The factors determining the erosiveness of natural sands are summarised. Using these relationships, it is shown that the damage produced in engines tested under controlled environments can be related to laboratory erosion data.

Consideration of methods of minimising erosion indicates that there is little scope for use of materials better than the martensitic steels and nickel alloys currently used in later stages of compressor blading. Estimates of the degree of protection to be obtained through use of intake filters indicate higher figures than are achieved in service. A helicopter trial subsequently showed that this is due to failure to achieve the filtration efficiencies given in controlled laboratory testing.



STAGE 1 STAGE 2

FIG.1 TYPICAL EROSION OF ROTOR BLADES IN A CIVIL ENGINE

I. Introduction

Severe damage can be caused in gas turbine engines due to ingestion of solid material varying in size from sub micron dust to pebbles and stones. Particles smaller than about 1000μm are usually termed dust or sand and continued ingestion of such material can lead to progressive erosion of engine components. This damage is usually confined to the compressor and can occur irrespective of the engine size or type i.e. whether centrifugal or axial flow. In extreme cases, the erosion can involve removal of sufficient material to cause components to be mechanically unsafe but it is more often manifested by modification of aerodynamic profiles leading to reduced efficiencies. In the case of axial blading of small engines, edge radii can be as little as 50 to 120μm and the blade profiles can be cut back as shown in Figure 1. Initially, erosion can produce some improvement in engine performance as the blades are polished and sharpened. Further damage, however, causes progressive degradation and can eventually lead to loss of surge margin and inadequate power. Large engines tend to be less susceptible to erosion because the bigger blading can withstand a proportionately larger loss of material before being affected e.g. it has been calculated that losses of up to 3 mm in the edges of fan blading of large engines can be tolerated. This difference is, of course, partially offset by the higher airflow and ability to lift bigger objects.

Interest in the erosion of aero engines was intensified during the 1960s when helicopters became extensively used in desert environments. Overhaul lives were drastically reduced and it was necessary to replace compressor blading after relatively short periods of time(1),(2). In operations over South East Asia, it has been reported that overhaul lives of 1000 to 1600 hours were reduced to about 300 hours leading to annual costs of millions of dollars(3). British experience in North Africa was equally bad, overhaul lives being reduced from 1000 hours to as little as 75 hours.

Operation of civil aircraft from relatively clean airports although apparently less damaging, can also involve erosion damage because the cleaner conditions are offset by the greater number of flights demanded for economic operation. Comparatively severe conditions can be encountered during icy weather when it is necessary to grit the runways. Although efforts are made to ensure that the grit is large enough to remain on the ground, the particles tend to become splintered and broken up. Some airports are sited in inherently dusty locations and there have been occasions when engines have been severely damaged by dust ingested during ground manoeuvres. Such damage necessitates early removal of blading and incurs excessive cost through loss of operational usage as well as for the replacement parts. In a recent analysis of experience with BEA, it was found that ingestion of debris cost ~£250,000 of which about £170,000 was directly attributed to erosion of compressor blading(4).

As a result of these service problems, there has been extensive laboratory work to explore the erosion parameters in an effort to find ways of minimising the damage. Broadly, the approaches have been (i) studies of mechanical behaviour to find ways of designing to avoid potentially erosive situations, (ii) development of materials and coatings having a good erosion resistance; and (iii) filtration of the incoming air to remove the erosive particles. In this Paper, these approaches are considered with respect to service experience.

II. Factors that influence erosion

In laboratory studies of erosion, it is convenient to measure losses by weight and it has become conventional to express erosion as the non-dimensional quantity, weight loss per unit weight of sand impacted, designated by ε. However, significant damage to engines is through dimensional changes rather than weight losses, and volumetric erosion, ε_v, is a more relevant quantity which can be calculated as $\frac{\varepsilon}{\rho}$ where ρ is the density of the target material. Use of ε_v has the additional merit that it enables comparisons to be made of materials having different densities.

The magnitude of the erosion is dependent upon the conditions of impact and the mechanical properties of the erosive particles and target material.

Conditions of impact

In laboratory testing, considerable attention has been given to conditions of impact such as velocity, strike angle, duration of exposure and concentration of erosive particles.

Numerous investigations have been made of the influence of velocity and it is generally accepted that erosion is related to velocity (V) by the simple power law expression

$$\varepsilon = aV^{\alpha} \qquad \ldots.(1)$$

where a is a material constant. Most investigations have shown that the exponent, α, is 2 or more and recent work has indicated that it is ~2.3 for a wide range of materials(5),(6),(7). However, it is possible that some brittle materials may have a higher value. Unlike rain erosion, the threshold velocity, below which no erosion occurs, is very low and can be ignored in most engineering situations, e.g. a value of 5.3 m/s has been deduced for 600µm iron pellets against glass(8) whereas impact velocities in compressors are typically 250 to 450 m/s.

The dependence on strike angle is different for brittle and ductile materials. Brittle materials such as fibreglasses or ceramics, are most susceptible to impacts at 90° to the surface and the angle dependence can be expressed by a relationship of the form

$$\varepsilon_\theta = b \sin^{\alpha} \theta \qquad \ldots.(2)$$

where b is the erosion at 90° and can be derived from Equation (2) as aV^{α}.

Ductile materials such as plastics and many metals are more susceptible to glancing impacts. In cases where there is zero erosion for 90° impacts theoretical analyses(9),(10),(11) have shown that the situation can be represented by an expression which approximates to

$$\left.\begin{array}{lll} & \varepsilon_\theta = c \cos^{\alpha} \theta \sin^{\alpha} \frac{\pi\theta}{2\theta_o} & \text{for } \theta < \theta_o \\ \text{and} & \varepsilon_\theta = f \cos^{\alpha} \theta & \text{for } \theta > \theta_o \end{array}\right\} \ldots.(3)$$

where c and f are material constants, α is usually assumed to be 2.0 and θ_o is the angle of impact when the component of velocity parallel to the surface is zero after impact. In practice, most materials exhibit significant erosion for 90° impacts and it is usually assumed that this is due to a brittle component occurring at the same time as the ductile erosion. Equations (2) and (3) can be combined to give

$$\left.\begin{array}{l} \text{for } \theta < \theta_o \\ \qquad \varepsilon_\theta = b \sin^{\alpha} \theta + c \cos^{\alpha} \theta \sin^{\alpha} \frac{\pi\theta}{2\theta_o} \\ \text{and for } \theta > \theta_o \\ \qquad b \sin^{\alpha} \theta + f \cos^{\alpha} \theta \end{array}\right\} \ldots.(4)$$

This type of behaviour is exhibited by the engineering alloys commonly used in gas turbines (Figure 2).

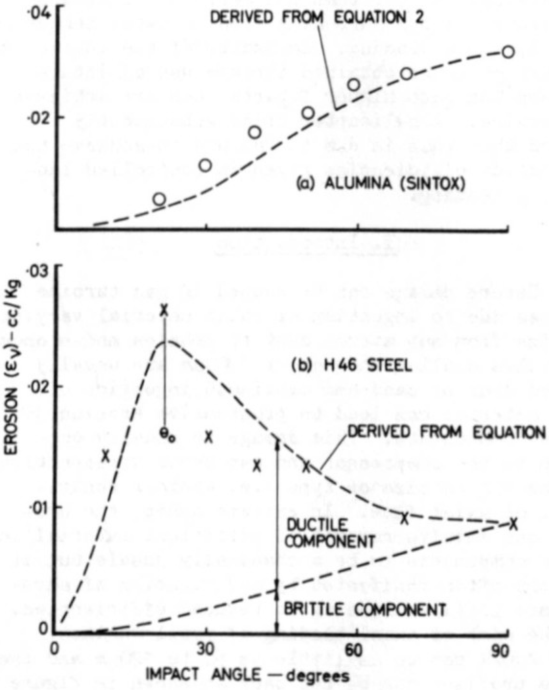


FIG. 2 INFLUENCE OF IMPACT ANGLE ON THE EROSION OF BRITTLE AND DUCTILE MATERIALS (60 125 µm QUARTZ AT 100 m/sec)

The relationships between erosion and angle of impact have been derived from tests on flat specimens but it has been shown(12) that erosion of curved surfaces can be estimated from such data by integration over the exposed area i.e.

$$\varepsilon = \frac{1}{2} \int_0^{\pi} \varepsilon_\theta \sin\theta \, d\theta \qquad \ldots.(5)$$

This was confirmed by tests on an aluminium cylinder tested with 60 to 125μm quartz at 100 m/s. However, it is often far from clear what the angle of attack actually is because the particles do not necessarily follow the air stream. In practice, large particles tend to ignore curved airflow whereas very small particles can follow it closely. Estimates(12) of the behaviour from a numerical analysis of the particle flow suggested that quartz particles above ~20μm will ignore the flow lines around flat plate and cylindrical targets at 100 m/s. However, the breakaway size is itself dependent upon features such as the material density, velocity and the radius of curvature of the flow.

Erosion can exhibit an incubation stage when there can be an initial weight gain as particles are embedded in the surface. This is followed by increasing losses which eventually stabilise at a constant rate. Soft materials such as aluminium and plastics commonly exhibit an extreme form of this behaviour. Harder materials can have a small incubation stage but it is negligible in nickel base alloys and the martensitic steels commonly used in later stages of compressors. From experimental observations it appears that deposition occurs throughout the process and it is reasonable to assume that deposition and erosion can be treated as separate components. If deposition is assumed to obey a power law dependence, the relationship between nett erosion and weight impacted (m) can be given by an expression of the form

$$\varepsilon = c - d\, m^{\beta - 1} \qquad \ldots.(6)$$

where β is less than 1. This is shown with respect to experimental data in Figure 3 using a value for β of 0.88.

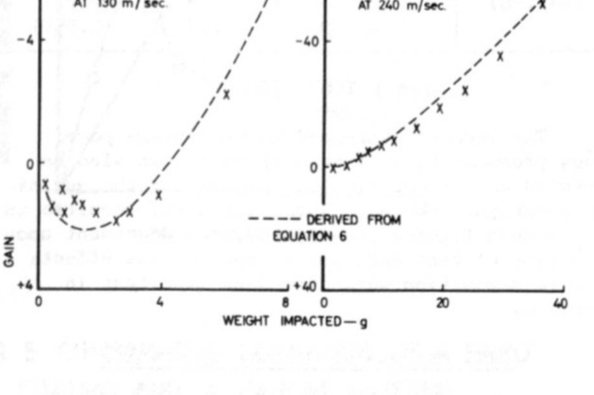


FIG. 3 INCUBATION BEHAVIOUR FOR TWO TYPES OF POLYURETHANE USING 125-150μm QUARTZ

Laboratory tests can exhibit a small concentration effect whereby erosion decreases with increased dust concentration. However, this is a relatively small effect involving a 50 per cent reduction in erosion for a 40/1 increase in concentration(13). Tests(14) on a small gas turbine using values of 1 to 7 mg/cu ft failed to detect any effect and it is usually neglected for practical purposes.

In compressors, temperatures up to ~450°C and stresses up to 200 MN/m² can occur and it has been necessary to determine the influence of these parameters. Temperature, (T), can raise or lower erosion depending on the material involved and it has been shown that the dependence can be related to the elongation at fracture, e

$$\varepsilon_T = \varepsilon \frac{e}{e_T} \qquad \ldots.(7)$$

so that increased ductility is associated with less erosion(12). In one of the few studies of the effect of tensile stress, it was found that values of up to 300 MN/m² produced little change to the erosion(12).

Material properties

For the impacting particles, the properties that influence erosion are essentially size, density, friability, hardness and sharpness. Studies of a wide range of natural and synthetic sands(5) have shown (i) erosion is dependent on particle size, (ii) quartz tends to be the most erosive constituent in natural sands so that the erosiveness of a given location can be characterised by quartz content; and (iii) the quartz content tends to decrease with particle size so that fine size ranges tend to be relatively innocuous. Thus, the erosiveness of sand from a given geographic location can be estimated from its size distribution (ϕ) and quartz content for a given size (Q_d) using the expression

$$\varepsilon = \int_0^{\phi(d)} \varepsilon_d \, Q_d \, d\phi \qquad \ldots.(8)$$

where ε_d is the erosiveness of a given particle size (d). The relationship between erosion and particle size is itself dependent upon the impact conditions and properties of the target material. Ductile materials exhibit increasing erosion with particle size up to a critical size beyond which no further increase occurs and it remains constant. Brittle materials can exhibit continuously increasing erosion according to a simple power law(13). With regard to the relationships between quartz content and particle size, it is interesting to note the similarity between the three samples from different geographic locations shown in Figure 4.

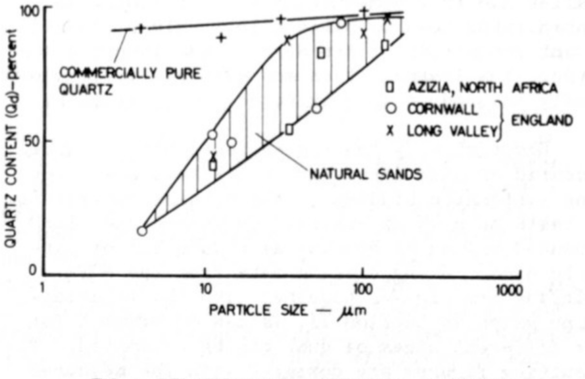


FIG. 4 RELATIONSHIPS BETWEEN QUARTZ CONTENT AND PARTICLE SIZE

In general, it can be seen that there was less than 50 per cent quartz present in particles smaller than 10μm whereas there was over 90 per cent in material bigger than 100μm. In using relationships such as in Equation (8) it should be noted that chemical analyses alone are insufficient to characterise the material and it is also necessary to identify the constituents mineralogically, e.g. a high Al_2O_3 content does not necessarily signify the presence of hard abrasive alumina. Samples of lateritic sands from South East Asia although having relatively high Al_2O_3 and SiO_2 contents, were found to be very friable and relatively innocuous as regards erosiveness. However, other problems were incurred because the dust very readily deposited and built up on the blading to produce big losses in efficiency.

There is a very wide range of erosion resistance exhibited by different materials from the very susceptible materials such as glass (100 cc/kg for 125 to 150μm quartz at 800 ft/s and 90° impacts) to the engineering alloys such as Nimonic 90 at 0.6 cc/kg. However, testing of the types of material typically used in compressors, has shown that they exhibit similar weight erosion i.e. 4.6 mg/g. Thus, a close approximation of the volumetric erosion can be obtained from use of the relevant density. This approach has been shown to be valid for alloys of aluminium, titanium, nickel and martensitic steels.

Various attempts have been made to relate erosiveness to other mechanical properties such as hardness, tensile strength, ductility and impact energy. However, these have met with only limited success such as the correlation given by Equation (7) and there is no generally accepted relationship in current usage.

Correlation with engine testing

Correlation of the erosion produced in engine tests with laboratory data can only be achieved satisfactorily if the impact conditions and nature of the erosive material are known. From consideration of the behaviour of particles in an airstream(12) discussed in 'Conditions of impact', it seems reasonable to assume that particles large enough to cause significant damage are uninfluenced by the airflow so that the impact conditions are dictated by features such as the velocity relative to the target, and subsequent rebound behaviour. There is considerable evidence that in multi-stage compressors, the particles impact in early stages, splinter and impact again in later stages. Towards the end of the compressor the particles tend to be projected into the outer annulus and are generally smaller due to fragmentation so that damage is concentrated towards blade tips. Unless a significant proportion of the dust avoids impact altogether, the fragmentation and multiple impacts are likely to produce an unexpectedly high erosion.

Comparatively few engine tests have involved measured erosion losses and there have been even less systematic studies of the erosion parameters. In tests on a 45 hp engine, Montgomery and Clark(14) produced values of erosion as a function of particle size. Using erosion data from the NGTE whirling arm rig(5), together with the relationships given in Section II, values of erosion for the different sizes of dust can be estimated. The resulting figures are compared with the measured erosion in the rotor and diffuser, where it is reasonable to assume that multiple impacts will not occur, and a reasonably good correlation is obtained (Table I). Similarly, tests on a Rover 1S/60 rotor by Duke(15), at different velocities, also correlate with the estimates.

Engine	Test condition	Erosion - mg/g	
		Measured	Estimated
45 hp engine (Ref.14)	0 - 74μm	7.0 - 8.8	6.8
	0 - 43	6.0 - 8.0	4.0
	0 - 15	1.2 - 2.0	1.4
	0 - 10	1.1 - 1.5	1.0
	0 - 5	0.7 - 0.6	0
Rover 1S/60 Rotor (Ref.15)	14μm, 180 m/s	1.12	1.01
	275	0.82	0.63
	370	0.48	0.45

Table I

In most tests on aero engines, weight losses were not measured and it is necessary to use a correlation factor to relate estimated erosion to measured power loss. Here it must be noted that power losses can be caused by deposition as well as erosion and it is necessary to consider measurements after cleaning and removal of the deposits. In Table II, such comparisons are made using losses for 0 to 1000μm dust as a datum for T56 and T58 tests, and 0 to 200μm for the T63 tests. Having obtained the correlation factor, losses can be estimated for the finer dusts giving reasonably close correlation with the measured values.

Engine	Test dust μm	Percent power loss/kg ingested	
		Measured	Estimated
T56 (Ref.16)	0 - 1000	0.70	-
	105 - 210	0.84	0.75
	0 - 80	0.15	0.11
T58 (Ref.17)	0 - 1000	2.95	-
	0 - 200	1.82	1.41
	0 - 40	0.53	0.46
T63 (Ref.18)	0 - 200	4.95	-
	0 - 80	5.15	2.2
	0 - 20	0.78	0.55

Table II

The losses, expressed as percentage power loss produced by unit mass of sand, can also be treated as a susceptibility factor for the engine in question. However, some caution is required in using such figures because they are dependent upon the type of test dust and do not include effects due to deposition which are most important in service.

III. Methods of minimising erosion

It is usually difficult to minimise erosion by design changes without penalising other aspects of the engine performance e.g. substantial improvements could be achieved by the use of thicker blading but only modest increases can actually be tolerated without undue aerodynamic losses (~25µm in blading of the Rolls-Royce Gnome engine). In addition, engines are usually designed to achieve a target performance and apart from features such as the siting of the intake, erosion is only given consideration after unfavourable operational experience. At this stage, it is difficult to make design changes and attention is given to use of improved materials and filtration of the intake.

Materials and coatings

Considerable efforts have been made to discover materials with good erosion resistance but these have met with very little success. In fact, the nickel superalloys and martensitic steels commonly used in the later stages of axial compressors have been found to be the best available engineering materials (both exhibit erosion of ~0.6 cc/kg for 125 to 150µm quartz at 800 ft/s). The only materials that are substantially better are hard ceramics such as hot pressed silicon nitride (0.2 cc/kg), boron carbide (0.2 cc/kg) and KT silicon carbide (0.3 cc/kg). However, it is expensive to produce blades in these materials and they are very fragile when impacted by larger particles. In tests with the NGTE whirling arm rig, a hot pressed silicon nitride specimen disintegrated when impacted by several 500 to 850µm quartz particles at 240 m/s. In some cases it is possible to improve the situation if denser materials can be tolerated e.g. BEA substituted titanium for aluminium alloy in early stage blading of Spey engines to obtain a 2/1 improvement in erosion resistance for a total weight increase of 18.3 lb in the first three stages of blading.

No outstandingly successful coatings have been discovered to date and little or no improvement can be obtained over the nickel based alloys. One of the best available tungsten carbide coatings was found to improve the erosion of H46 steel under glancing impacts but was worse for 90° impacts (Figure 5).

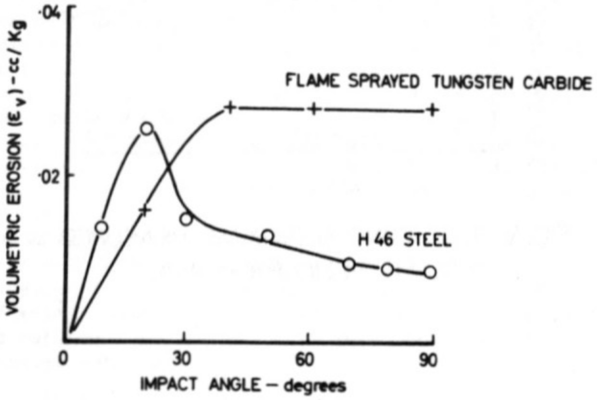


FIG. 5 COMPARATIVE BEHAVIOUR OF A HARD COATING AND A PARENT MATERIAL (60-125 µm QUARTZ AT 100 m/sec)

As a result of this type of experience it appears that an increase in thickness of the base material, by an amount equal to that of the coating, would be almost as effective and considerably cheaper. However, protection of more susceptible materials is a viable proposition and successful systems have been developed. In Figure 6, the behaviour of a nickel coating on fibreglass is shown in comparison with the parent material and it can be seen that an improvement of 19/1 has been achieved. This erosion resistance is similar to that of the aluminium alloy RR58, but inferior to that of H46 steel.

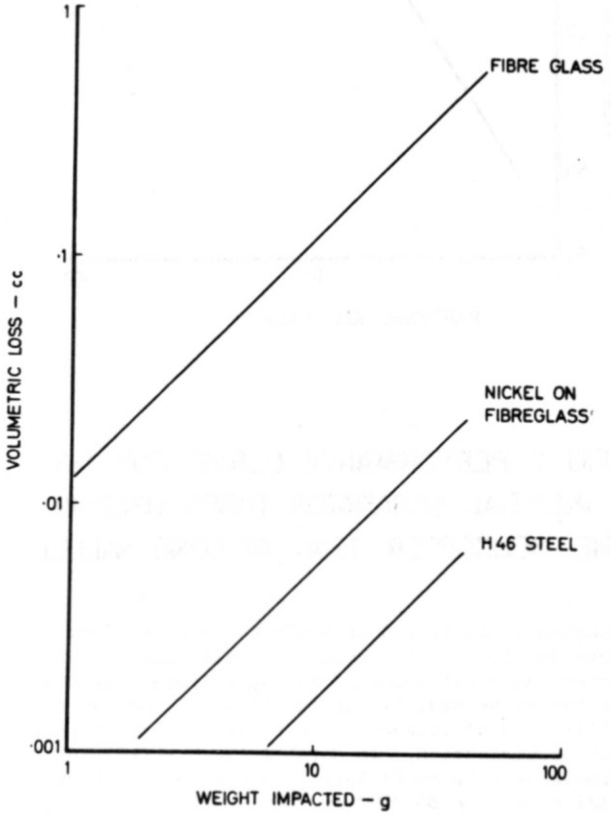


FIG. 6 COMPARATIVE BEHAVIOUR OF A NICKEL COATING AND PARENT MATERIAL (125-150 µm QUARTZ AT 130 m/sec)

Filtration

Weight penalties and the size of installations are such that filtration systems cannot be seriously considered for civil transport. However, the small engines used in helicopters and hovercraft can be filtered and a variety of methods have been explored. Of these, systems based on banks of small inertial separators have been favoured because they have the merit that they are self cleaning, can be relatively light weight and involve modest pressure drops. Good performances can be obtained with very high efficiencies as shown in Figure 7. However, the actual improvements in life produced by these systems have been substantially less than would be expected from consideration of the degree of filtration. Approximate estimates of the anticipated improvements can be made by consideration of the overall filtration efficiency for a representative type of dust distribution. In North African work, dust clouds were found to have size distributions very similar to the BS 1701 coarse: 1970 distribution for which an individual inertial separator tube had a bench efficiency of 96.5 per cent. If particle size effects are ignored this should give a life improvement of 29/1 whereas experience with different types of condition has shown that figures of around 5/1 are actually achieved(18),(19),(20). More detailed consideration of the influence of particle size worsens the disparity because filters tend to pass only the smaller particles and these are intrinsically less erosive as well as having a lower quartz content. This more precise estimate can be made from consideration of the unfiltered damage which is given by

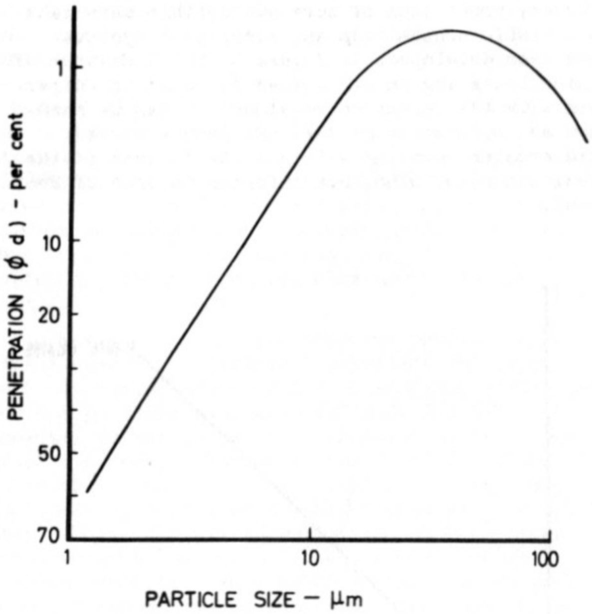


FIG. 7 PERFORMANCE CURVE FOR THE INERTIAL SEPARATOR TUBES USED IN THE HELICOPTER TRIAL AT LONG VALLEY

$$\int_0^{\eta(d)} \varepsilon_d \, Q_d \, d\eta$$

and the filtered damage which is

$$\int_0^{\eta(d)} \varepsilon_d \, \phi_d \, Q_d \, d\eta$$

The resulting improvement has been calculated to be 60/1.

In an effort to resolve this disparity, a trial was conducted at the Long Valley test ground (Hampshire, England) using a Scout helicopter with and without filtration (Figure 8).

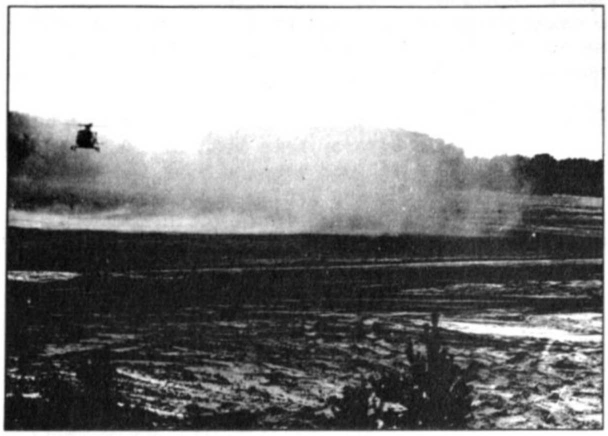


FIG. 8 DUST CLOUD PRODUCED BY A SCOUT HELICOPTER AT 6M HEIGHT

Sampling probes were fitted upstream and downstream of the filters so that dust concentrations, size distributions and filtration efficiencies could be measured. Dense dust clouds were created with concentrations of up to ~7 mg/cu ft for hovering heights of 5 to 20 ft (Figure 9).

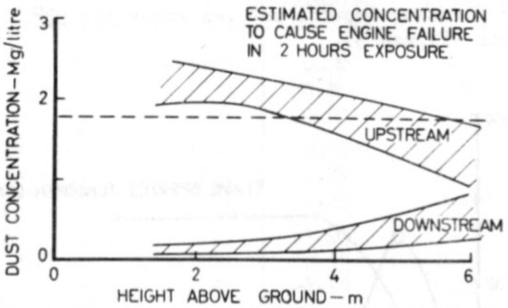


FIG. 9 DUST CONCENTRATIONS MEASURED IN SCOUT HELICOPTER TRIAL.

The size distributions of the clouds were relatively coarse, so that the filters should have performed above expectations based on the finer distributions. However, the results showed that the performance was below expectations because (i) the upstream and downstream samples exhibited similar size distributions when it would be expected that larger proportions of the big particles should be removed, and (ii) the overall efficiency was substantially lower than the bench value for a finer type of dust (Figure 10).

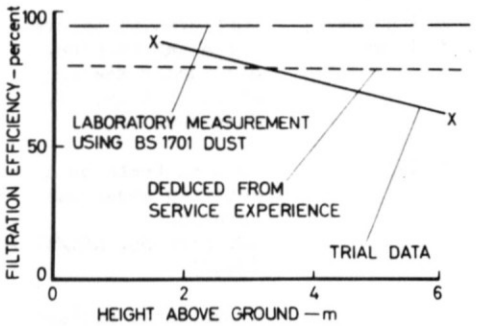


FIG. 10 TOTAL FILTRATION EFFICIENCIES MEASURED IN THE HELICOPTER TRIAL AT LONG VALLEY

These low efficiencies are consistent with service experience as shown in Figure 10, and with other types of helicopter filtration system(18), (19), (20), so that it may be concluded that filtration systems can fail to achieve design performance in flight. This behaviour may be due to features such as the effect of the rotor down wash or to inadequate scavenge flow in some of the individual tubes. Clearly, further attention is required in this area.

IV. Conclusions

Laboratory studies of sand erosion have shown that the extent of the damage is dependent on the impact conditions and the properties of both the target and the abrasive materials. Equations describing the most important parameters have been summarised and it has been shown that the relative behaviour of engines under different conditions can be estimated from laboratory data.

The nature and extent of the erosion damage can vary according to the size of the engine and nature of operation i.e. whether civil or military. In civil aircraft, erosion is produced during a relatively large number of flight cycles and problems arise through replacement of worn parts rather than hazardous operation due to mechanical unreliability. The most viable method of minimising the problem appears to be through substitution of materials or coatings having better erosion resistance. Unfortunately, there are no usable materials better than the martensitic steels and nickel alloys currently used in the later stages of axial compressors. In some cases it is possible to replace light alloys with more resistant but heavier materials.

Vehicles such as helicopters and hovercraft are specifically designed to operate off unprepared airstrips and can create dense dust clouds and incur severe erosion. Under service conditions the lives can be reduced drastically and it is essential to improve the situation. Unlike civil aircraft, the smaller engines can be fitted with filters and it is possible to design a system giving a big improvement in life. Unfortunately, it appears that operation of such installations in flight involves unexpectedly low efficiencies.

Acknowledgement

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