PRACTICAL HELICOPTER DESIGN

SOME ESSENTIAL ENVIRONMENTAL PARAMETERS

BY

COMMANDER M. F. SIMPSON, C.ENG., M.I.MECH.E., M.R.AE.S., R.N.

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THE SPECIAL CASE OF THE HELICOPTER

Introduction

This article is an attempt to identify the severe environments that are a direction function of the helicopter's versatility, and which do not apply in the same degree to fixed-wing aircraft. Whilst in general these problems may also be relevant to other VTOL designs, the scope here is limited to the type of conventional helicopter with which we are now familiar. No practical investigations have been undertaken, and discussion has been drawn from the considerable quantitative data which is available on this subject, and from what is already known to us. This article is not intended to be a comprehensive effort to establish general guidelines; its object is simply to illuminate the problem.

FIG. 1—SCOUT NEAR KUCHING, BORNEO

The Helicopter Environment

A helicopter can only rival a fixed-wing aircraft if its VTOL capability is exploited. In airstrip to airstrip operation, the provision of the VTOL design features are a handicap which will make a helicopter non-competitive. The practical helicopter is therefore best employed working from random locations, convenient only for the direct delivery and collection of different payloads (FIG. 1). This often involves operation from unprepared sites, and may demand landing, hovering or taking off in rotor generated debris. In addition, the performance limitations of a rotor system restrict flight to a fairly modest altitude band, making it impossible to climb above the weather. These two factors mean that a helicopter can sometimes be faced with the unavoidable choice of either operating in a hostile environment or not operating at all. This is a situation to which a fixed-wing aircraft usually has some options.

Self-induced particle damage was first highlighted in the recent war in S.E. Asia, mostly in the specific field of erosion damage to engines. Natural particle hazards were not given full recognition until the development of flight control systems had made flight in cloud technically feasible, but only if icing conditions were avoided—a requirement which still requires very restrictive margins of safety to guarantee.

It is therefore considered that these special environmental situations warrant recognition and inclusion in specifications for helicopters, which at the moment still reflect their fixed-wing genesis. The aircraft and engine manufacturers require guidance from the customer on the degree of protection he requires for each environmental hazard. This must be forthcoming to initiate and support the research and development required to underwrite the success of the next generation of helicopters.

AIRBORNE PARTICLES DUE TO ROTOR DOWNWASH

FIG. 2—WESSEX HOVERING IN SAND

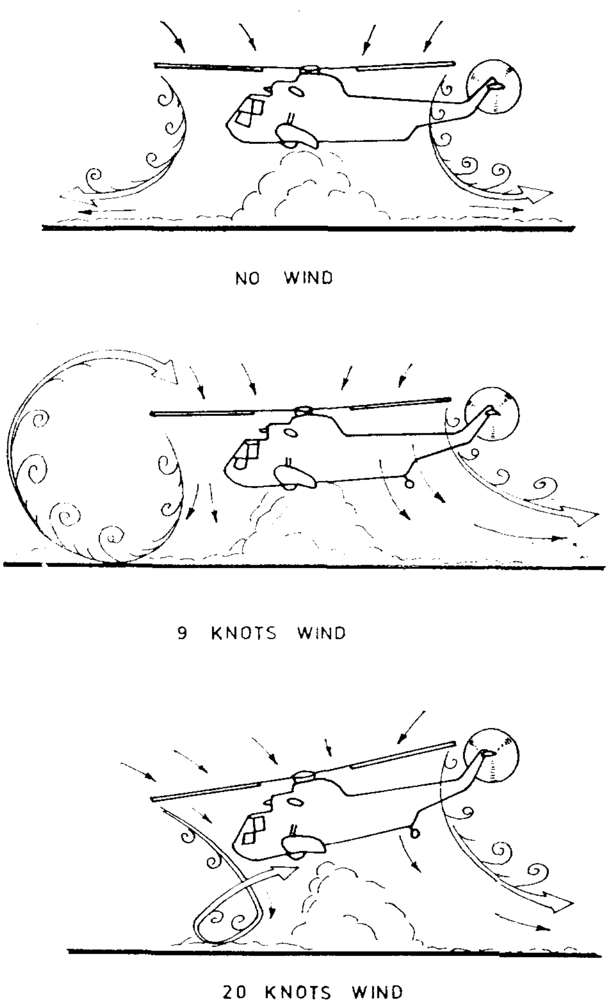

FIG. 3—DOWNWASH FLOW SYSTEM SURROUNDING A SEA KING TYPE HELICOPTER HOVERING IN GROUND EFFECT (STIRGWOLT)

Rotor Recirculation in Ground Effect

When a simple air jet is directed vertically at the ground, part of its energy is converted into pressure causing a radial acceleration of air flow outwards from the impingement area. This results in high velocity air flowing near and parallel to the ground, and a static pressure gradient at the ground surface.

When a helicopter hovers in ground effect, the rotor downwash causes a similar situation, except that it is accompanied by recirculation creating the classic vortex pattern of the flow field surrounding a hovering helicopter (FIG. 2). Film evidence from sand trials (1,2) suggests that the overall field diameter/height ratio remains within 3 to 5 for hovering up to 100 feet. This downwash pattern can be substantially changed when hovering against a natural wind (FIG. 3).

Thus the air velocity along the ground is a function of the build-up of dynamic pressure, which in turn is a function of downwash or wake velocity. Simple momentum considerations show that the fully developed wake velocity has twice the velocity of the induced velocity at the rotor disc. Fradenburg has shown that, when hovering in ground effect, airflow velocities along the ground can be expected which are of the same order as wake velocities predicted by simple momentum theory (3). It can also be shown that the indicated mean induced velocity depends solely on the rotor disc

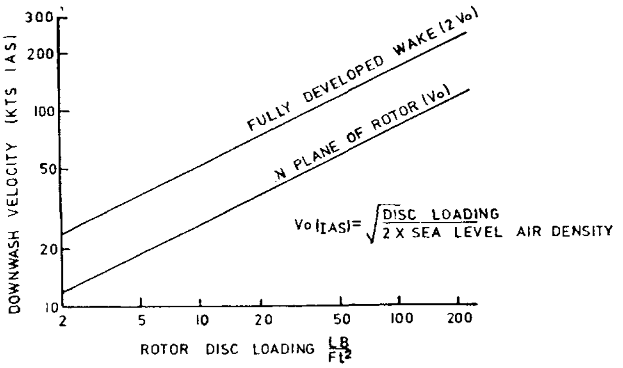

FIG. 4—DOWNWASH VELOCITIES ACCORDING TO SIMPLE MOMENTUM THEORY FOR ROTORS OUT OF GROUND EFFECT

loading, and this relationship is shown in FIG. 4. This establishes a direct relationship between rotor disc loading and airflow velocity along the ground.

Experimental results on this theme are shown in FIGS. 5, 6, 7 and 8. In the case of a current helicopter with a disc loading of about 7·5lb/ft^2, these arguments predict local ground velocities of approximately 45 knots. This is severe gale speed, and puts some perspective into the basic question. It can also be seen that as helicopters became progressively heavier and faster, any increases in disc loadings necessary to achieve this will increase the airflow velocity scrubbing the surface below and further aggravate the problem.

The surface particles in the area underneath the hover will thus be subjected to aerodynamic forces which may induce them into the main vortex system enveloping the helicopter. This will depend on their physical characteristics and surface adhesion. A study of the ability of different VTOL lift systems to energize various types of terrain shows that helicopters can be expected to move snow, dry sand, water, loose dirt and vegetation, but not crushed rock, soaked sand, packed clean clay or sod (4).

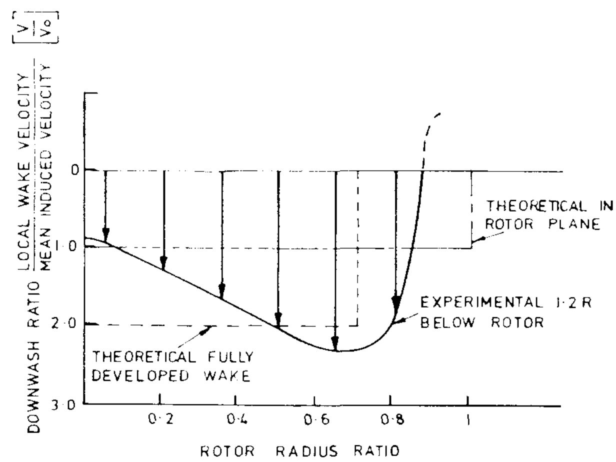

FIG. 5—COMPARISON BETWEEN THEORETICAL AND EXPERIMENTAL MODEL DOWNWASH VELOCITIES FOR ROTOR OUT OF GROUND EFFECT

Field trials have also identified considerable variations in particle concentration within the vortex system (2,5) and this distribution needs to be understood when establishing relevant design features, such as the optimum location of engine air intakes. Each particle, after being accelerated into the airflow by virtue of the kinetic energy imparted to it, will have its own terminal settling velocity. Reference to Stokes Law, considered to be relevant to particles up to about 85μ (6) (one micron (μ) = 10^{-3}mm or 0·00004 inches in diameter), shows how the larger particles will settle at a much faster rate, reducing their chance of being drawn through the complete vortex pattern. This could also explain the cut-off in the size distribution pattern at some critical altitude noted in desert

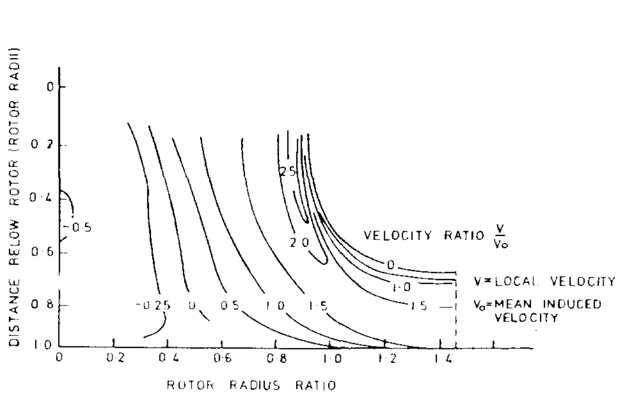

FIG. 6—VELOCITY CONTOUR MAP FOR A ROTOR 1·0 RADIUS ABOVE GROUND

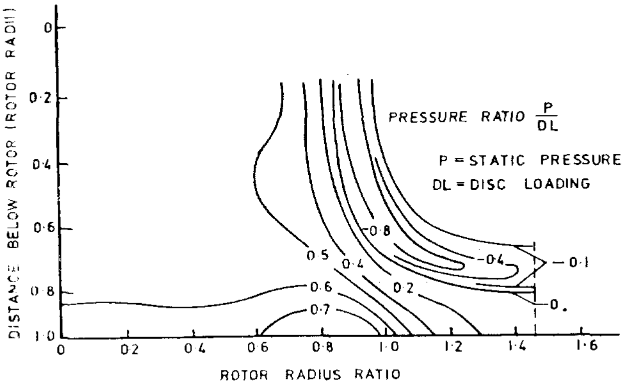

FIG. 7—STATIC PRESSURE CONTOUR MAP FOR ROTOR 1·0 RADIUS ABOVE GROUND

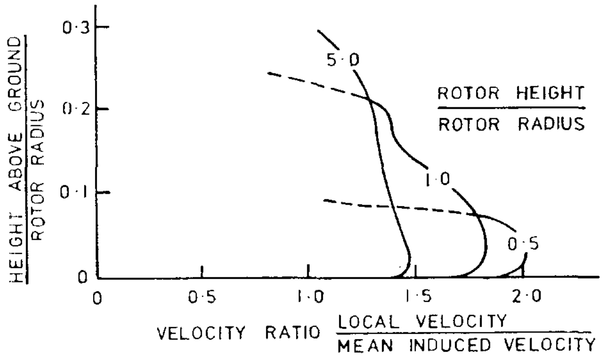

FIG. 8—VELOCITY PROFILES ALONG GROUND MEASURED AT A DISTANCE OF $1\frac{1}{2}$ ROTOR RADII FROM ROTOR CENTRE LINE

trials (2). It is also supported by the observation that after departure of a helicopter from a desert area, the size of particles remaining in suspension decreases as the dust cloud clears up (7).

The Effect of Recirculation

The problem of airborne particles due to rotor downwash is therefore one of a relatively large mass of slow-moving air recirculating through the rotors carrying with it debris swept from the surface underneath, some of which will make physical contact with the helicopter. The recirculation pattern is one of a dome-shaped region of low velocity in the centre with the main downwash being pushed outboard and upwards. Surface wind has the important effect of further altering local concentrations of particles inside the cloud by distortion of the vortex pattern relative to the helicopter. The main effects are various degrees of damage to the helicopter and its engine(s), shown as some form of temporary or permanent performance loss, obstruction of pilots vision,

FIG. 9—SEA KING HOVERING OVER SEA

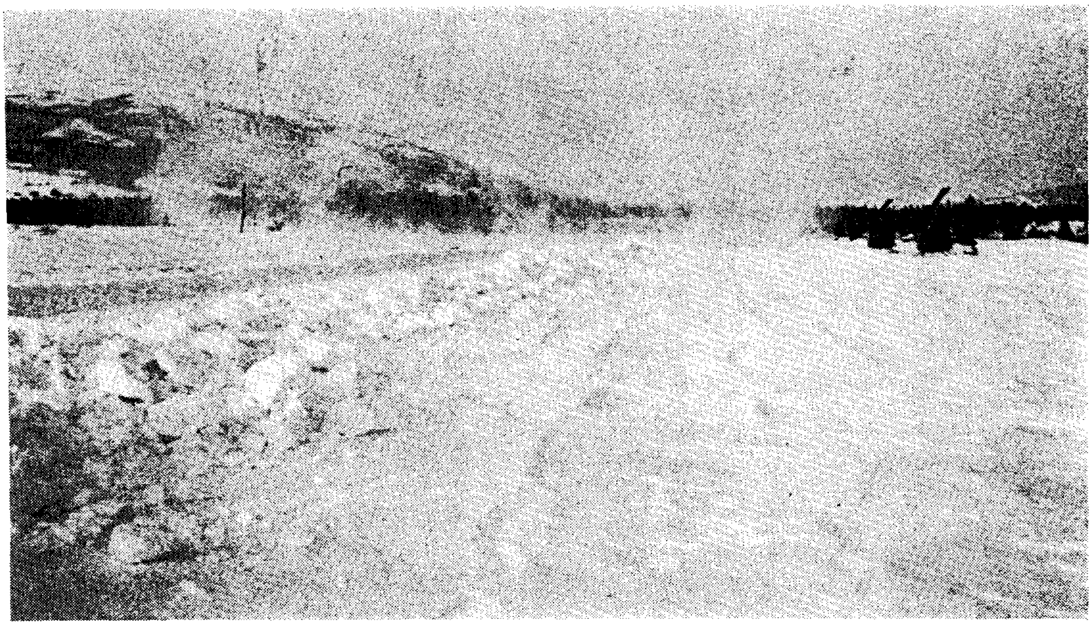

FIG. 10—WESSEX LANDING OVER SNOW

FIG. 11—WESSEX OVER U.K. TERRAIN DISTURBED BY VEHICLES

contamination of closed systems by penetration of seals on exposed rams, and difficulty in achieving effective operational concealment.

FIGS. 9, 10, and 11 show examples of clouds raised whilst landing or hovering over different surfaces. Various flying techniques have been established and are practiced to minimize the effect of the cloud raised during landing and take off, but the problem still exists particularly when two or more helicopters are operating in company. Where the task requires an established hover to be held, as an anti-submarine sonar operation, personnel winching, external cargo collection or delivery, and deployment or recovery of troops from a low hover, it is often impossible to avoid prolonged immersion in the cloud. This makes tolerance to the expected conditions an important design feature.

Sand and Dust

This problem is usually associated with high temperatures and solar radiation. It is not confined to the classic desert regions of blown sand as it can be experienced in all the semi-arid regions of the world and also seasonally in many agricultural areas, particularly when the surface layer has been disturbed. In most areas soil exhibits a greater tendency to stick together on the surface giving a 'pavement' which, in general, varies between $\frac{1}{4}$ inch and 2 inches thickness. The concentration of the sand or dust cloud varies drastically with the amount of disturbance the 'pavement' has experienced. If intact, relatively high wind velocities are required to raise dust. If destroyed, a dust haze can be formed by a mere breeze (8). This accounts for the concentration of dust usually found in areas of high activity, and has a particular significance for helicopters involved in any military operation (FIG. 11).

In general, the main constituent of natural sand and dust, and also the one with the severest erosive properties, is silicon dioxide (SiO_2 or silica) occurring in its most common form of the mineral quartz. The high quartz distribution in natural dust is probably because it is one of the hardest constituents, and abrasive movement between the particles over a period of time reduces the softer constituents in size. Quartz has a characteristic sharp-edged crystal structure, a s.g. of 2·66, and a micro hardness of about 1000 kg/mm^2. It varies in appearance from transparent to opaque and is often coloured brilliantly by various contaminants (FIG. 12). It is probably the most widely occurring mineral, and chemically one of the most inert and inactive (6). Thus it is convenient, in any attempt to quantify the abrasiveness of natural dust, to use quartz as the standard abrasive particle.

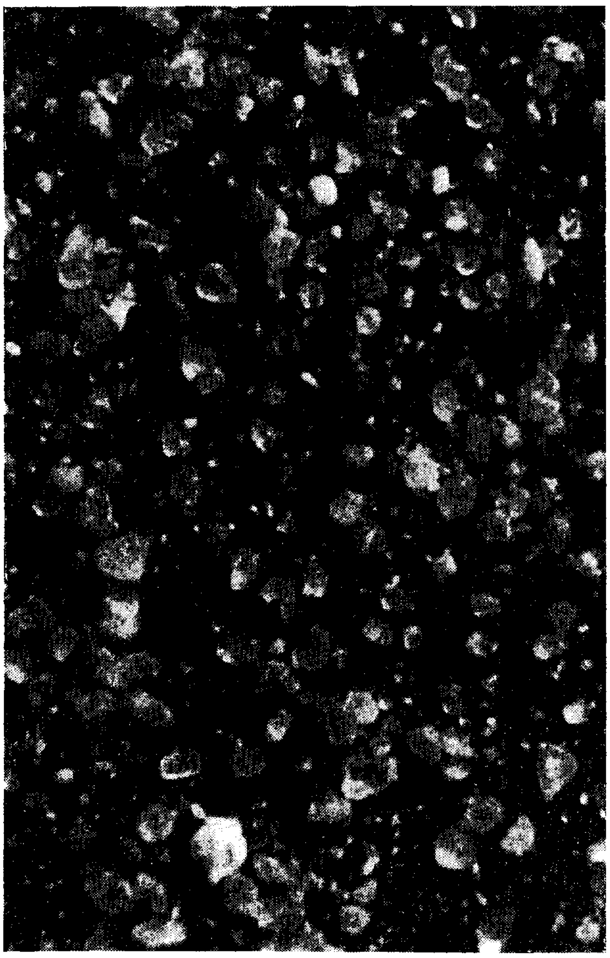

FIG. 12—TYPICAL SAND SAMPLE × 50

There appears to be only limited test evidence on particle concentration and size distribution inside a rotor generated dust cloud. Those trials which have been carried out are slightly at variance, and also indicate a problem of repeatability, particularly with the quality of the terrain below. There are difficulties in guaranteeing true isokinetic collection of particles, and compensating for variations in natural conditions such as humidity, wind strength and temperature.

The most comprehensive results found during this study were from the 1966 A. & A.E.E. Boscombe Down trial of a Wessex helicopter in North Africa (1,2). Over quartz type sand, peak concentrations at the engine intake ranged from about 50 mg/ft^3 in a 10-foot hover to about 10 mg/ft^3 in a 20-foot hover, with

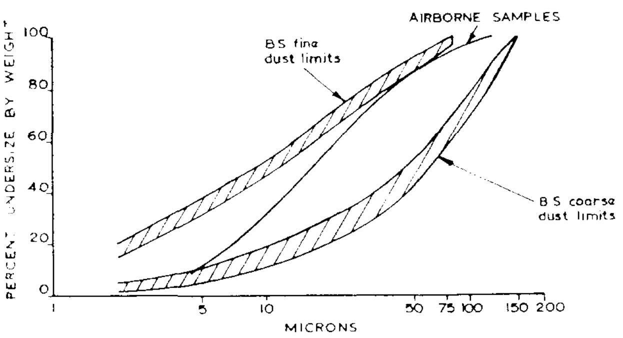

FIG. 13—SIZE ANALYSIS LIMITS OF BS 1701 TEST DUSTS AND TYPICAL WEIGHT DISTRIBUTION OF AIRBORNE SAMPLES COLLECTED UP TO 40 FEET (WESSEX SAND TRIALS)

concentration falling to virtually zero in a 100-foot hover. The results also showed no consistent tendency for a change in size distribution up to 40 feet. Generally, the maximum sized airborne particle was 115μ over areas where the largest ground sample measured was 250μ, suggesting separation of the larger particles somewhere between their initial displacement by the rotor downwash and the engine intake entry plane. The general trend of sand concentration and size distribution is shown in FIGS. 13 and 14.

It can be seen that the size distribution pattern of the airborne samples tends towards the size distribution of the larger particles in British Standard 1701 (1970) fine dust (BS1701 fine dust is similar to SAE J 726a fine grade dust). In the next section it will be shown that according to NGTE tests (9), the lower limit of particle erosive significance may be about 20μ, with an upper limit of something under 100μ, due to the 'plateau effect'. If this is so, then BS1701 fine dust would appear to give a very close approximation to the erosive significant content of rotor generated dust clouds. This important conclusion must be tempered by the fact that at this time there is little other evidence to support it. Similar tests with an H-21 helicopter (5) gave similar trends, but in general experienced a larger size distribution of airborne samples. Hovering an H-34 helicopter within 100 feet of this test produced a fivefold increase in the measured concentration.

Although the geometric specification for BS1701 dust is closely defined as it was developed to control air-filtration standards, some variation in its composition is allowed. Its material can consist of either quartz or undecomposed feldspar which in some forms is softer than quartz. Thus if BS1701 dust is to be used for erosion testing, the material content needs to be stated. Rig and chamber tests required by the Military Vehicles Experimental

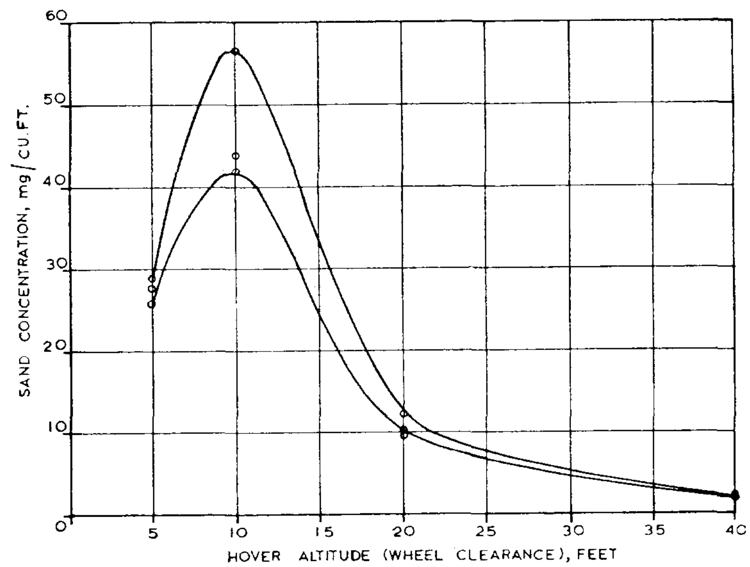

FIG. 14—AIRBORNE SAND CONCENTRATION AGAINST ALTITUDE SHOWING TOP AND BOTTOM LIMITS OF SCATTER EXPERIENCED DURING WESSEX SAND TRIALS (MEASURED AT ENGINE INTAKE)

Establishment use BS1701 size ratings with the additional specification of a 98 per cent. quartz content. (As it is often difficult to obtain this concentration, concessions are sometimes made to allow 94 per cent. quartz with the remainder aluminium oxide) (10).

The Nature of Solid Particle Erosion

Sand and dust under the influence of dynamic forces are powerful erosion agents and, in order to quantify damage within the boundaries of a system, erosion is usually expressed as an erosion factor (ε) in milligrams per gram.

$$\text{Erosion Factor } \varepsilon = \frac{\text{Unit weight loss}}{\text{Unit weight of dust impacting}}$$

This is simply weight of material removed by unit weight of impacting particles. However, in comparing erosion of different materials, it is sometimes more meaningful to use a volumetric loss, if the problem is manifested by modification of a geometric profile, rather than by weight loss; this applies particularly to compressor blading.

Erosion by solid particles received little disciplined study before about 1960. Work by Tilly, Sage, and Goodwin at the National Gas Turbine Establishment in the late 1960's gave general understanding of the influences of the main parameters governing erosion, and allowed service behaviour to be estimated from the use of descriptive equations (9). Some of these relationships are shown in Fig. 15. Although the resulting expressions gave satisfactory correlations with experimental evidence, the laws governing the influence of velocity and particle size were not fully explained at this stage. Further work by Tilly has now produced an explanation for the erosion of ductile materials (11).

The NGTE results showed:

(*a*) Erosion is dependent on the properties of the dust such as hardness, sharpness and mineral composition. For natural dusts, erosion appears to be determined by the quantity of quartz present, according to the expression

$$\varepsilon = 0{\cdot}012\eta_q$$

where ε is for normal impact against steel at 420 ft/sec, and η_q is percentage quartz by weight.

(*b*) Particles less than 5μ caused little damage, and it was suggested that for helicopter engine filtration requirements it might be unnecessary to remove particles smaller than 20μ.

(*c*) Erosion is dependent on size and velocity of the impacting particles. For the ductile materials examined, including aluminium alloy (12), erosion rate stabilized at a discrete particle size, giving a plateau effect for each impact velocity. (There is evidence to suggest that with quartz particles above 300μ, the erosion rate will start to increase again, but this size of particle is considered to be above that which can be entrained in the vortex system and so it is not significant to helicopters.)

(*d*) Total erosion is independent of dust concentration and, within sensible limits, is a direct function of total weight of dust impacted for a given particle size and impact speed. This makes it easier to relate specification requirements to qualification tests.

Rotor Blade Erosion

Unprotected light-alloy blades are particularly prone to erosion by dust, heavy rain and sea spray. The effect is most severe at the tip. Leading edge

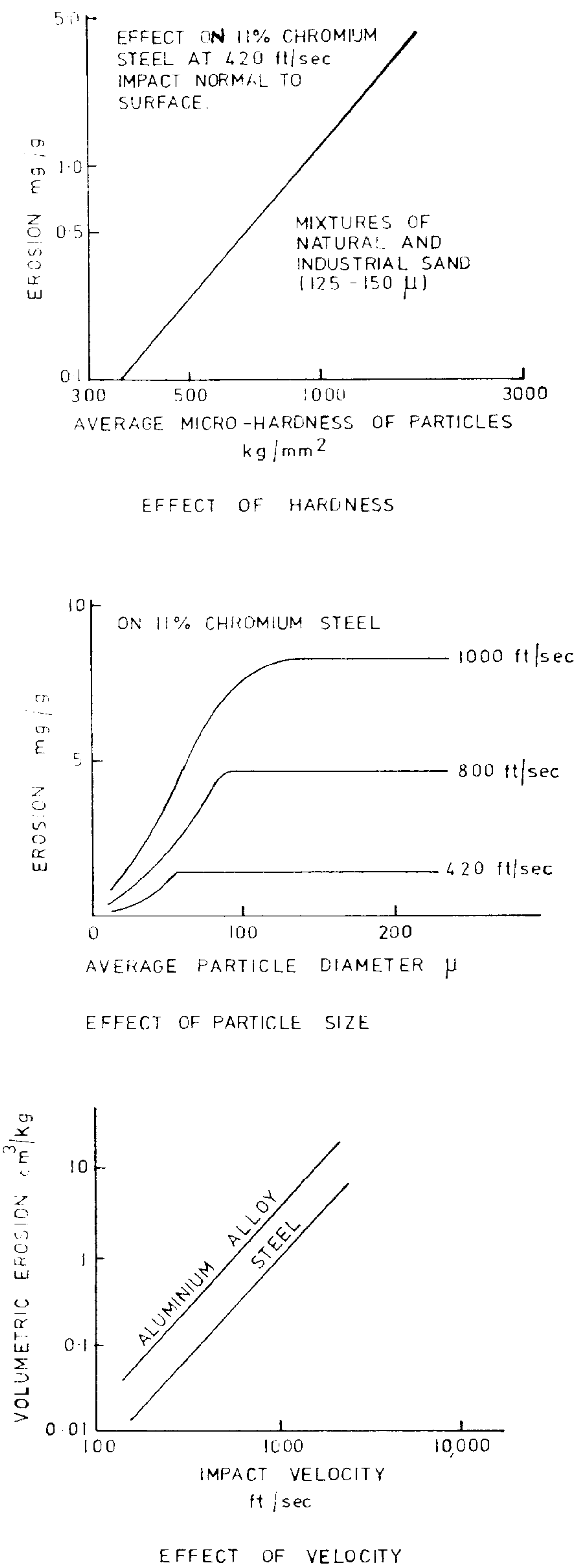

FIG. 15—INFLUENCE OF PARTICLE HARDNESS, VELOCITY, AND SIZE ON EROSION (GOODWIN, SAGE, AND TILLY)

roughness caused by erosion can be expected to lead to premature blade stall, vibration, and attendant large changes in pitching moment. This would in turn lead to an increase in the amplitude of blade oscillating torsional loads which could result in increased fatigue damage to the inboard control mechanism (13). It is not known if erosion critically affects oscillatory blade (flapping, bending) stresses in the main rotor blade, although some research on this is now taking place (14).

Dust erosion follows the pattern already described under the previous heading. For rain erosion, experimental results show that with a constant drop size distribution and impact velocity, the steady erosion rate is directly proportional to the rate of rainfall above a certain characteristic threshold speed for each material, below which erosion does not occur. The rate of erosion of a material varies proportionally with about the third and the fourth power of the velocity, which explains the concentration of rain erosion damage at the extremities of rotor blades. Little is known of the mechanism of rain erosion, but *ad hoc* testing has supplied much information which has established certain design parameters. The effect of hail impact is also a matter of important consideration; although the problem is more serious than rain erosion, it is offset by the fact that hail occurrence is much less frequent and more restricted in extent than rain. Consequently rain erosion assumes primary importance as a design requirement (15).

Examples of sand and heavy rain erosion of unprotected main rotor blades are shown in FIGS. 16 and 17. This was a problem