

# 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.

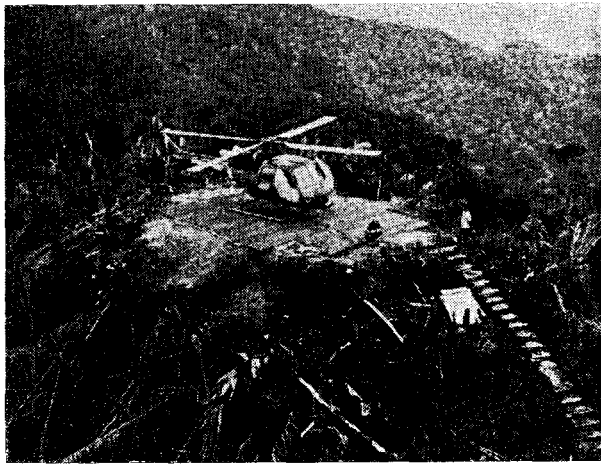


FIG. 1—SCOUT NEAR KUCHING, BORNEO

#### 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

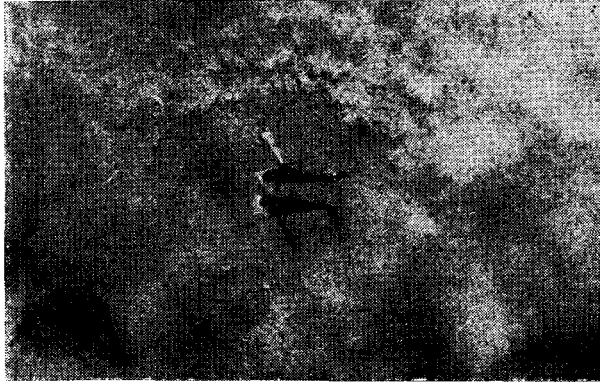


FIG. 2—WESSEX HOVERING IN SAND

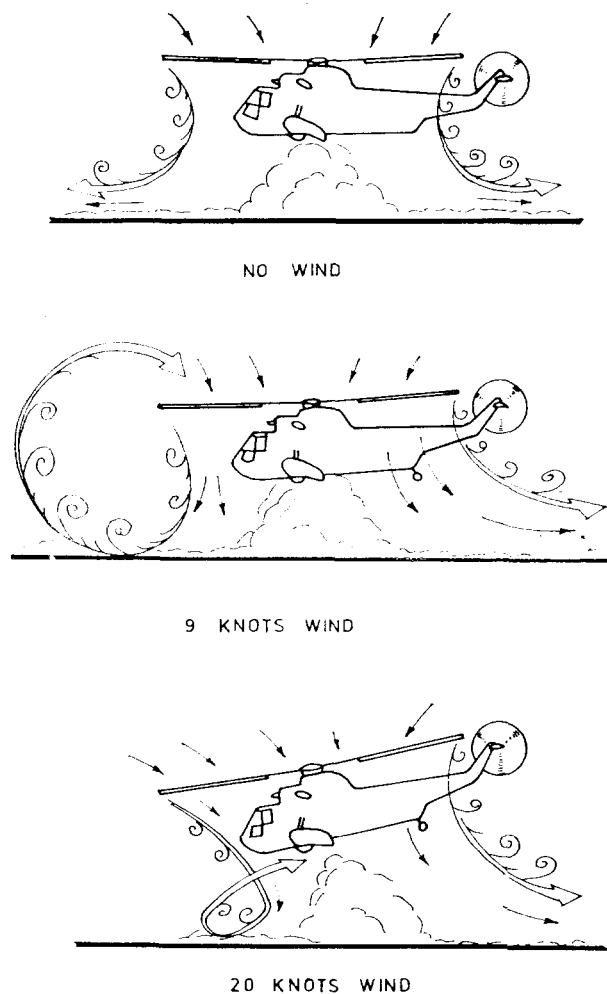


FIG. 3—DOWNWASH FLOW SYSTEM SURROUNDING A SEA KING TYPE HELICOPTER HOVERING IN GROUND EFFECT (STIRGWOLT)

### 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

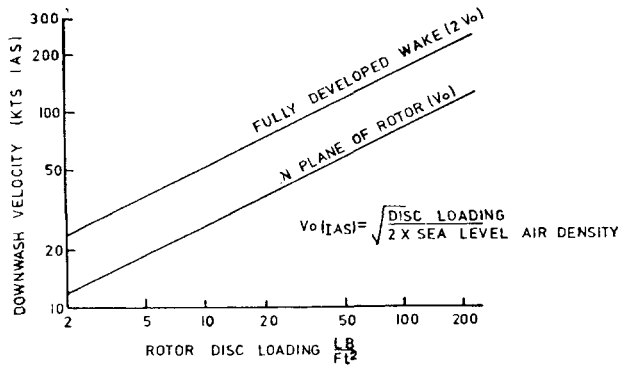


FIG. 4—DOWNWASH VELOCITIES ACCORDING TO SIMPLE MOMENTUM THEORY FOR ROTORS OUT OF GROUND EFFECT

tion. 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

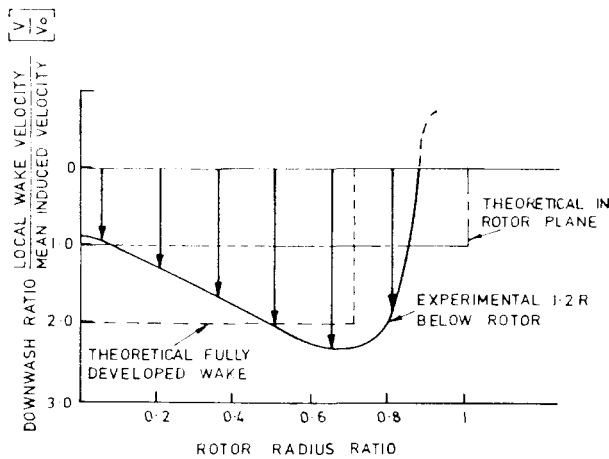


FIG. 5—COMPARISON BETWEEN THEORETICAL AND EXPERIMENTAL MODEL DOWNWASH VELOCITIES FOR ROTOR OUT OF GROUND EFFECT

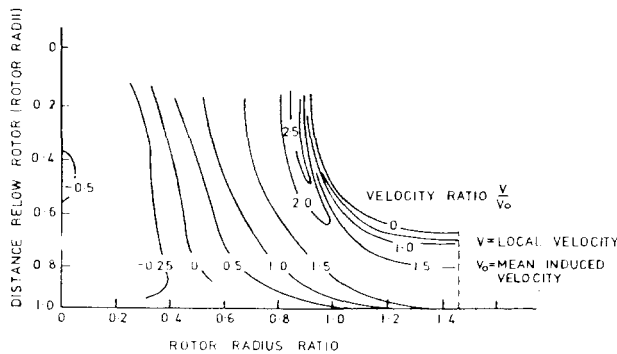


FIG. 6—VELOCITY CONTOUR MAP FOR A ROTOR 1.0 RADIUS ABOVE GROUND

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<sup>2</sup>, these arguments predict local ground velocities of approximately 45 knots. This is severe gale speed, and puts some perspective into the basic question. 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<sup>-3</sup>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

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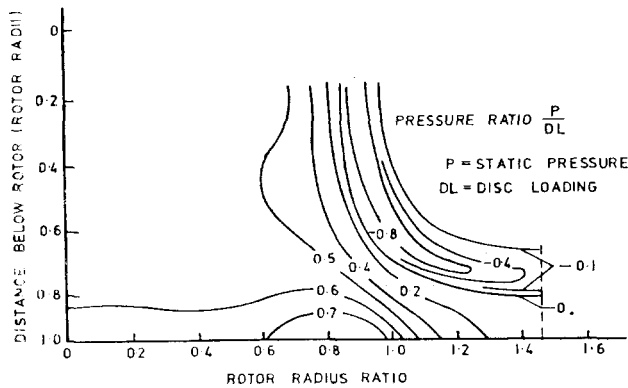


FIG. 7—STATIC PRESSURE CONTOUR MAP FOR ROTOR 1.0 RADIUS ABOVE GROUND

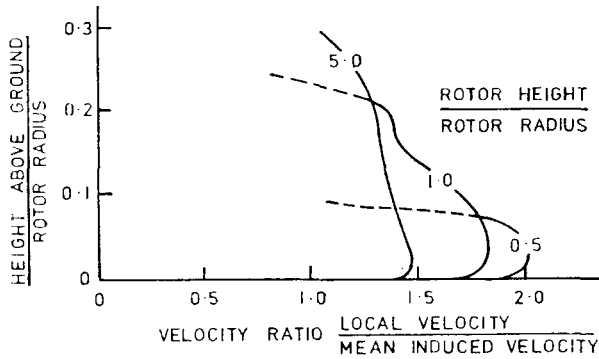


FIG. 8—VELOCITY PROFILES ALONG GROUND MEASURED AT A DISTANCE OF  $1\frac{1}{2}$  ROTOR RADII FROM ROTOR CENTRE LINE

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

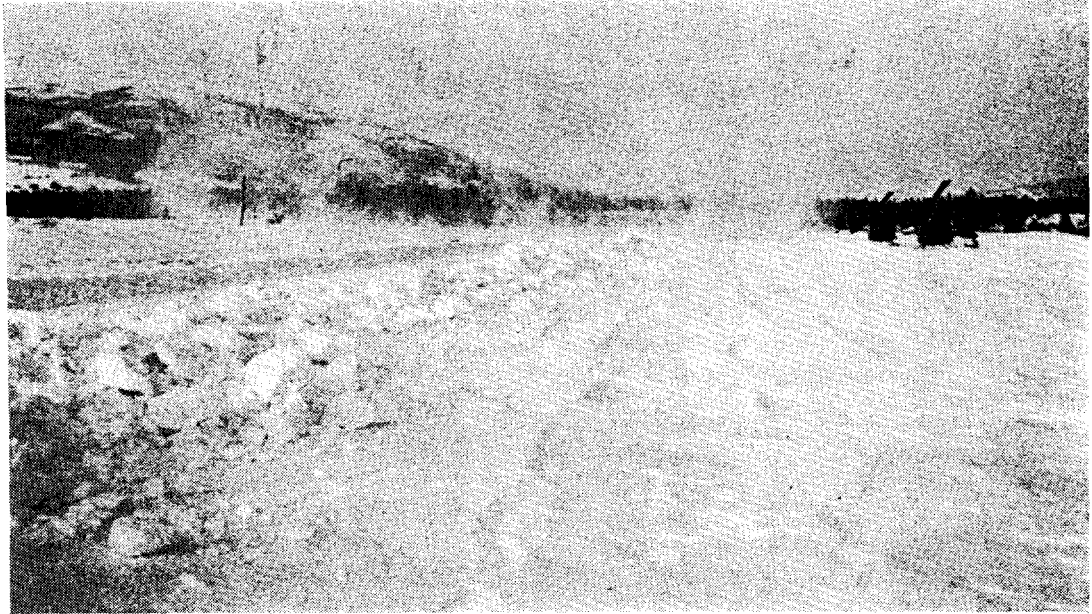


FIG. 10—WESSEX LANDING OVER SNOW



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 ( $\text{SiO}_2$  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<sup>2</sup>. 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

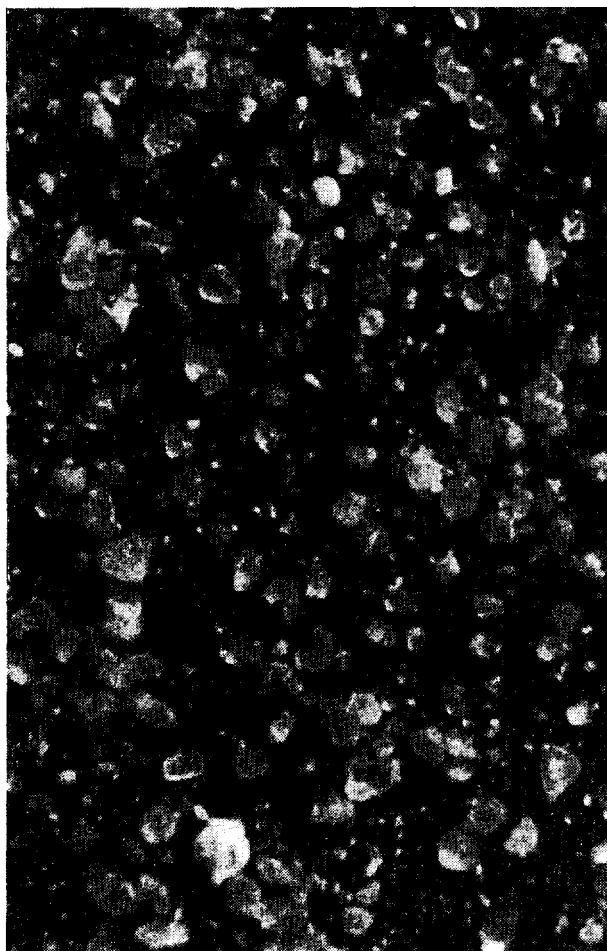


FIG. 12—TYPICAL SAND SAMPLE  $\times 50$

inactive (6). Thus it is convenient, in any attempt to quantify the abrasiveness of natural dust, to use quartz as the standard abrasive particle.

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<sup>3</sup> in a 10-foot hover to about 10 mg/ft<sup>3</sup> in a 20-foot hover, with

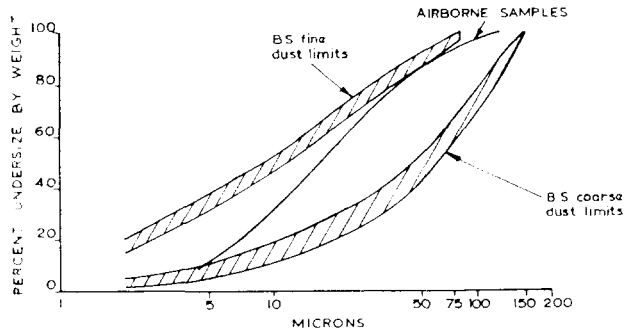


FIG. 13—SIZE ANALYSIS LIMITS OF BS 1701 TEST DUSTS AND TYPICAL WEIGHT DISTRIBUTION OF AIRBORNE SAMPLES COLLECTED UP TO 40 FEET (WESSEX SAND TRIALS)

concentration 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  $20\mu$ , with an upper limit of something under  $100\mu$ , 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

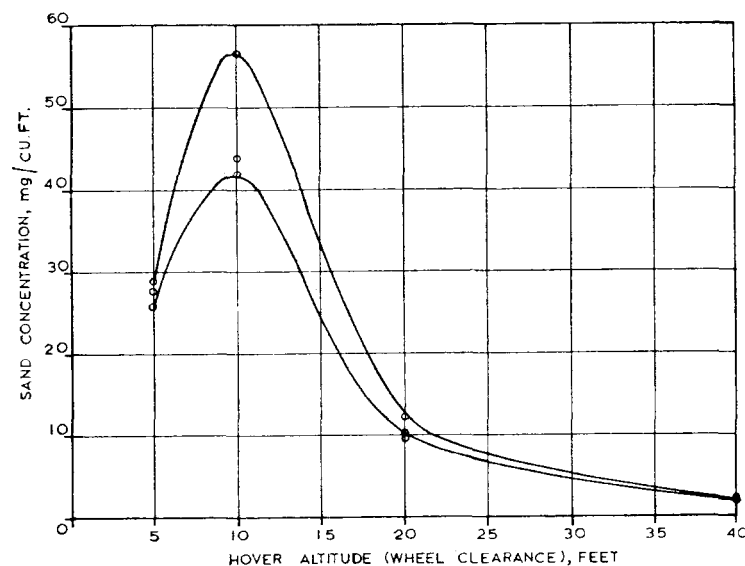


FIG. 14—AIRBORNE SAND CONCENTRATION AGAINST ALTITUDE SHOWING TOP AND BOTTOM LIMITS OF SCATTER EXPERIENCED DURING WESSEX SAND TRIALS (MEASURED AT ENGINE INTAKE)

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  $115\mu$  over areas where the largest ground sample measured was  $250\mu$ , suggesting separation of the larger particles somewhere between their initial displacement by the rotor down-wash and the engine intake entry plane. The general trend of sand



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 ( $\epsilon$ ) in milligrams per gram.

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

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
 
$$\epsilon = 0.012\eta_q$$
 where  $\epsilon$  is for normal impact against steel at 420 ft/sec, and  $\eta_q$  is percentage quartz by weight.
- (b) Particles less than  $5\mu$  caused little damage, and it was suggested that for helicopter engine filtration requirements it might be unnecessary to remove particles smaller than  $20\mu$ .
- (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  $300\mu$ , 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



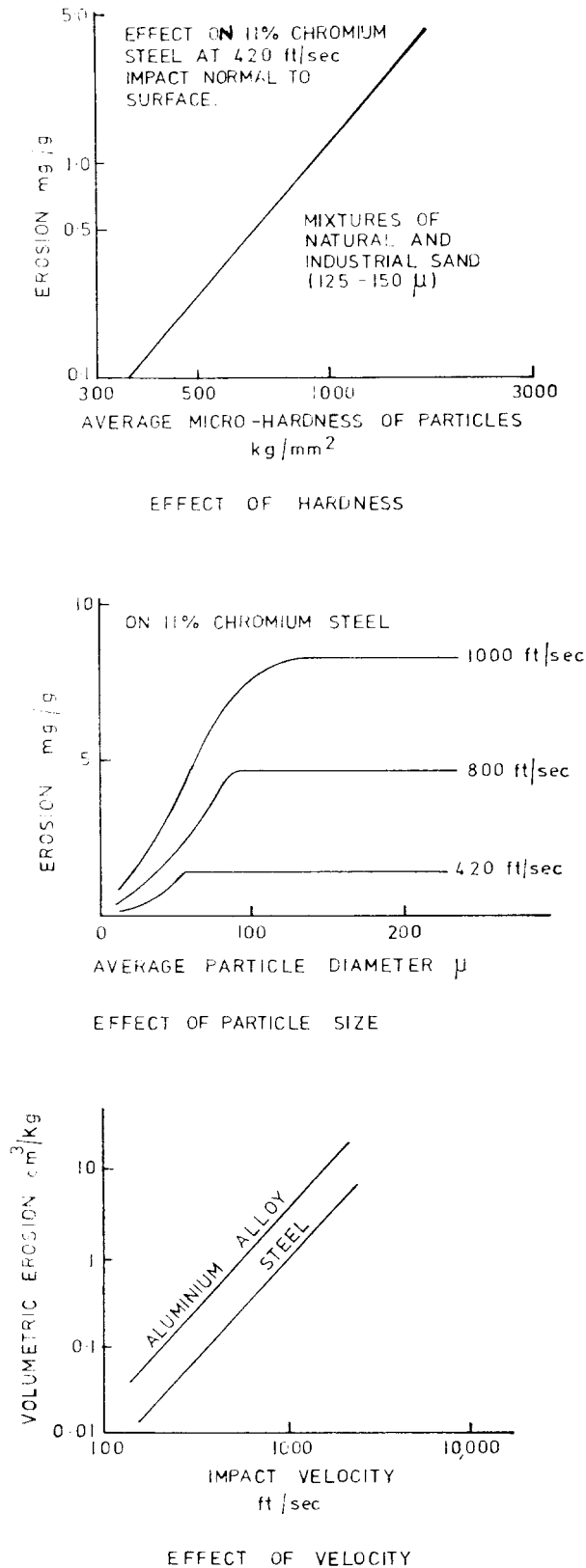


FIG. 15—INFLUENCE OF PARTICLE HARDNESS, VELOCITY, AND SIZE ON EROSION (GOODWIN, SAGE, AND TILLY)

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

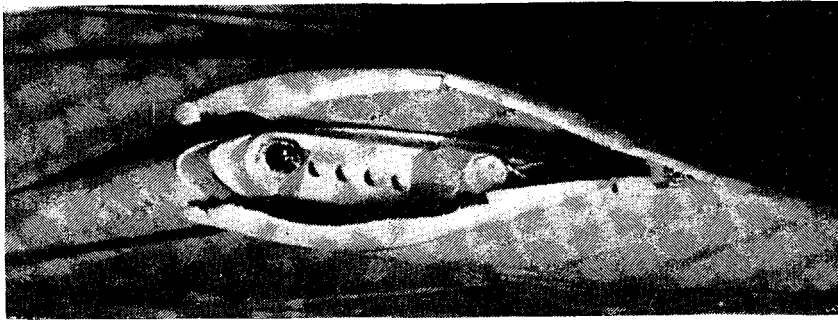


FIG. 16—SAND EROSION OF ROTOR BLADE TIP CAP

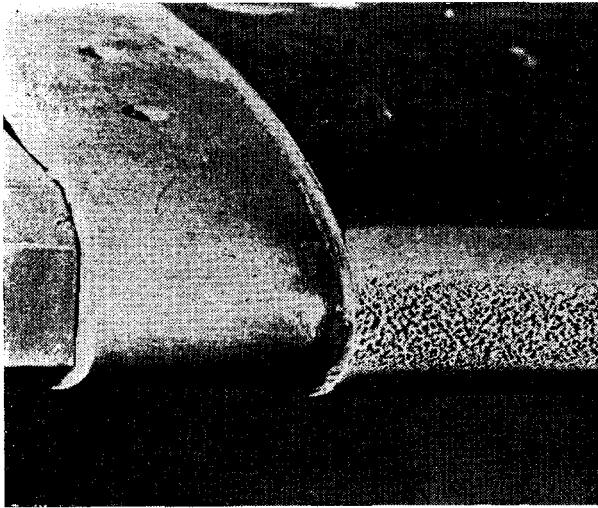


FIG. 17—RAIN EROSION OF ROTOR BLADE LEADING EDGE

of the 1960's which is now under control. There was some delay in producing a solution because the materials which gave best rain erosion resistance (stainless steel or titanium) did not give particularly good sand resistance. British Service helicopters which use light-alloy main rotor blades now use polyurethane rubber leading edge protection. This gives good sand resistance, reasonable rain resistance and, with the current self-adhesive material, offers relatively simple in-field replacement (16). Although this protection can still be damaged by very heavy

tropical rain, many rotor blades are now achieving their lives due to properly maintained polyurethane leading-edge protection.

### Engine Erosion

The first generation of helicopter gas-turbine engines was based on a background associated with fixed-wing aircraft, which operate in relatively clean air. The problem of erosion damage was noticed shortly after the first turbine engine helicopters were deployed in hot countries, but efforts towards a solution were on a small scale and largely ineffective. The problem was only recognized as both obvious and serious after operational experience of U.S. helicopters in S.E. Asia showed erosion to be the main cause of unscheduled engine removals, often after only 10 to 20 per cent. of the normal time between overhaul (TBO) period. In the U.S.A., this stimulated immediate development and redesign to contain the problems in existing engines, and has established general guidelines applicable to future design. Because new gas turbine developments are continually promising extension on thermally limited TBO's, helicopter engines which were previously heat limited may become erosion limited unless positive advances against erosion are also made in parallel.

The main problem of engine erosion is alteration of the compressor aerofoils. Erosion leaves a well-known signature in helicopter engine compressors, and so it is not intended to describe the pattern in any detail other than to say that the particles tend to be centrifuged outwards, concentrating damage at the blade tips and stator roots. Besides jeopardizing the structural integrity of these parts, erosion causes a reduction in stall margin, a decrease in

power, and an increase in specific fuel consumption. Trials have suggested (1) that the size of particle liable to be ingested from a rotor-induced dust cloud will not be large enough to produce the leading-edge 'burring' characteristic of foreign object damage from other sources.

Montgomery and Clark determined engine-erosion rates as a function of dust particle size and concentration, with the erosion factor  $\epsilon$  appearing constant for any realistic dust concentration up to 13 mg/ft<sup>3</sup>. From this information they were able to predict engine life as being proportional to a constant, representative of the engine type, and inversely proportional to the product of the particle size and dust concentration (17). (Note: this does not agree with NGTE's 'plateau' observations.)

Bianchini and Koschman carried out dust erosion tests of a T-63, using selected sizes of coarse Arizona Road Dust. They found engine power decreased almost linearly with total dust ingested, apparently independent of dust concentration (see also sub-paragraph (d) of NGTE results under 'Solid Particle Erosion'). Tests at up to 10 $\mu$  had little effect, 0—20 $\mu$  was not severe, and 0—80 $\mu$  and 0—200 $\mu$  were both severe but not noticeably different (18). This supports the NGTE 'plateau' observations (sub-paragraph (c) of NGTE results).

Potential solutions to engine erosion appear to be:

- (a) Increased engine tolerance.
- (b) Air cleaning to some degree.
- (c) Location of engine intakes in zones of low particle concentration.
- (d) Combination(s) of above.

Research into increased engine tolerance has not yet produced significant results, so considerable work remains to be done in providing engine protection without unacceptable performance losses or complication. Any device placed in front of the engine to remove dust will obviously either have to be compatible with the other environmental requirements (anti-icing, snow, etc.) or be easily removable when these conditions are expected.



FIG. 18(a)—WESSEX TAKING OFF OVER STRAW STUBBLE

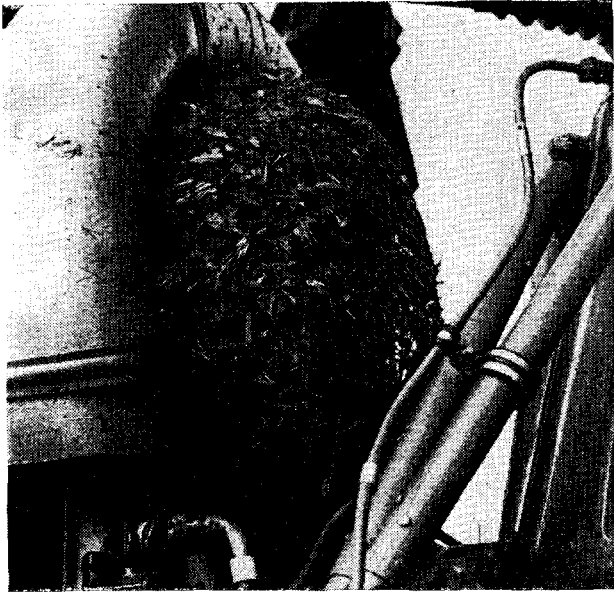


FIG. 18(b)—LOOSE VEGETATION OVER SCOUT INTAKE

### Surface Debris

This covers material that has a large surface area in relation to its mass (including a red carpet at a recent V.I.P. landing) allowing it to be energized by the rotor recirculation system. Damage to engines has been caused by natural and cultivated vegetation (FIGS. 18a and 18b), paper, rags, and sheet ice from footprint impressed snow. Whilst this hazard can be reduced by suitable preparation and selection of sites, it is always a problem when tactical landings are a requirement.

### Airborne Salt

For convenience, this section discusses the presence of sea-salt due to rotor induced downwash and to natural causes.

Information on the salt characteristics of the marine environment comes from two main sources: from work carried out at the cloud base by those interested in the role of salt nuclei in rain-forming mechanism (500 m upwards), and from work carried out at sea level by those with ship interests (deck to downtake level). Information about the area in between is very sparse and inconsistent.

Sea-salt in the air is encountered in two general forms, as aerosols and mists. Aerosols are particles of a few microns in diameter and originate from bursting bubbles associated with breaking waves; they are therefore a function of wind action on the surface of the sea. As wind speed and wave height increase, sea aerosol will increase in concentration and size distribution until a mixture of aerosol and mist exist together. Mists are also generated by the impact of waves against a hard surface and, in general, can

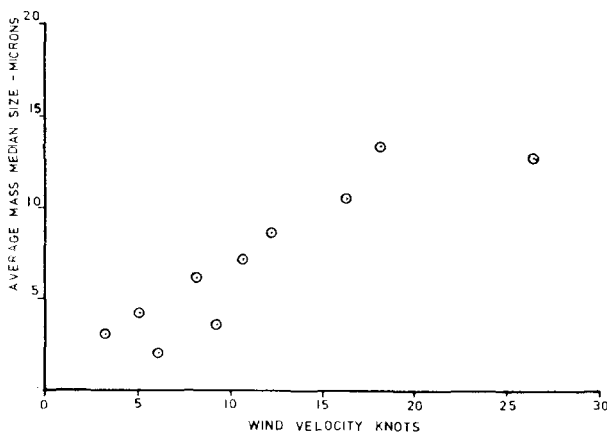


FIG. 19—AVERAGE MASS MEDIAN SIZE OF SEA-SALT AEROSOL AGAINST WIND VELOCITY THAT PRODUCED IT (N.A.E.C. DATA FROM SEA-LEVEL TESTS AT KEY WEST)

be said to consist of particles considerably larger than  $25\mu$ . Mists generated by a ship's bow will depend on sea state, and ship's course and speed (FIG. 20). Mists have a high fall-out rate and do not persist. Aerosols float in the air for extended periods of time and, although concentration will vary according to previous and prevailing wind speeds, it may be assumed that they are always present in a marine atmosphere.

These natural aerosol, at appreciable heights over the sea, contain particles from



FIG. 20—FORMATION OF SEA-SALT MIST BY SHIP'S BOW (H.M.S. 'ARETHUSA')

0.1 $\mu$  to 20 $\mu$  in size, with the peak in the mass size distribution increasing from about 1.5 $\mu$  at wind force 1 to 6 $\mu$  at wind force 7 (Beaufort Scale). Tests at Key West showed an aerosol concentration between 0.0016 to 0.0275 ppm by weight, with an average of 0.0113 ppm. FIG. 19 shows the relationship between average mass median size against wind velocity (20).

The critical relative humidity below which salt particles are dry is 75–76 per cent. Relative humidity in the 30-foot layer does not normally drop below 79 per cent., and therefore salt contacted in this region is likely to be in the form of liquid droplets of near saturated salt solution, density 1.2, salinity 25 per cent. (19).

Some U.S.N. data, sampled from a helicopter 10 to 30 feet above the sea, found particles of 150 $\mu$  to 500 $\mu$  with a 50 per cent. probability diameter in the range 20 $\mu$  to 90 $\mu$ , the quantity of large drops increasing sharply with wave height (19). This means that, by the accepted definition, a hovering helicopter will be enveloped in both mist and aerosol with a consequent large variation in particle size distribution. It has already been stated that the surface wind speed under the hover of a typical anti-submarine helicopter will be in the region of 65 knots (Force 12) which can explain the U.S.N. results. FIG. 9 shows a helicopter hovering over a relatively calm sea. Immediately underneath, there appears to be a low velocity region where the downwash is turned to form the outflow profile. Radiating out from this is a white frothy ring of agitated water, where the high velocity air scrubs the surface. It is here that the water droplets are formed and carried into the rotor recirculation system. Stirgwolt (21) refers to a slow motion movie study of this process, from which FIG. 3 was derived. This shows that, for the particular configuration shown, hovering into a 10-knot wind is the worst condition for the engines.

### The Effect of Airborne Salt

There are three distinct phases of helicopter use in which airborne sea-salt is significant. They are: whilst parked on flight decks or sea platforms, during transit flights at relatively low altitudes, and hovering in ground effect over the surface. The first two entail continuous exposure to aerosols and occasional exposure to mist, and the last continuous exposure to both. This exposure can cause:

- (a) Normal ambient temperature or aqueous corrosion in the airframe and in the compressor section of the engine.

- (b) Salt deposit on the transparencies.
- (c) Salt deposits on the rotor blades.
- (d) Salt deposits in the compressor.
- (e) High temperature corrosion or sulfidation of the engine hot section.

Normal temperature corrosion of aircraft in a marine environment is a problem which has received considerable attention in the Royal Navy. It was both recognized and reduced in the 1960's, mostly due to the lead taken by the Naval Aircraft Materials Laboratory who produced some effective and practical measures to contain the effect of corrosion on equipment already in service. It is therefore not intended to discuss this issue here, except to say that it is still with us and seems a fruitful area for full coverage in specifications. Many well-known problems could be avoided at the design stage.

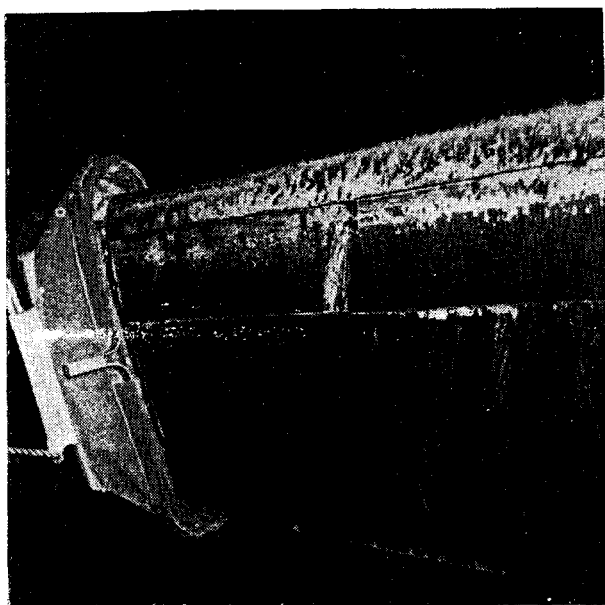


FIG. 21—SALT DEPOSITS ON UNDERSIDE OF ROTOR BLADE

Salt deposit on windscreens can lead to obstruction of vision during continuous hovering associated with anti-submarine operations as well as low level flight in rough weather. It occurs not only in hot weather but also in low temperature operation which requires use of heated windscreens for anti-icing.

There is significant *ad hoc* evidence over recent years that salt deposits on main rotor blades may effect oscillatory control loads and vibration in a similar way to erosion as already discussed (14). An example of salt deposits on a main rotor blade after low level flight over rough sea is shown in FIG. 21. The incident which led up to this occurred in January 1964,



FIG. 22—FORMATION OF SEA-SALT MIST BY HIGH WIND

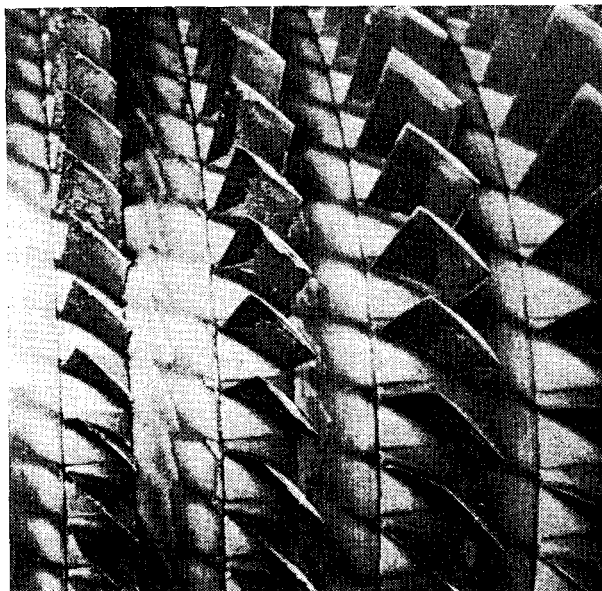


FIG. 23—SALT DEPOSITS IN COMPRESSOR

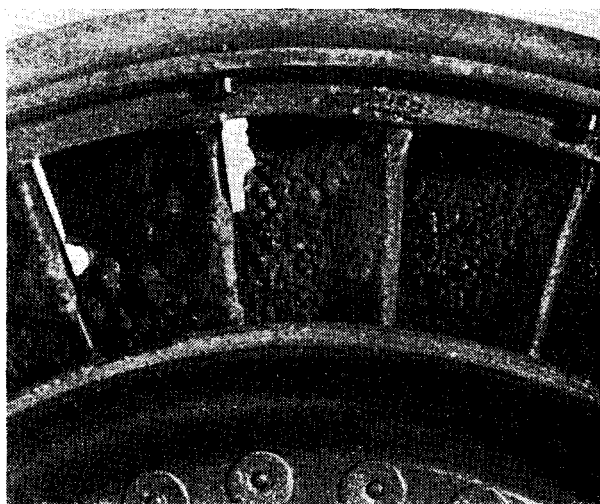


FIG. 24—SEVERE HOT CORROSION OF NGVs AFTER PROLONGED OPERATION IN MARINE ENVIRONMENT

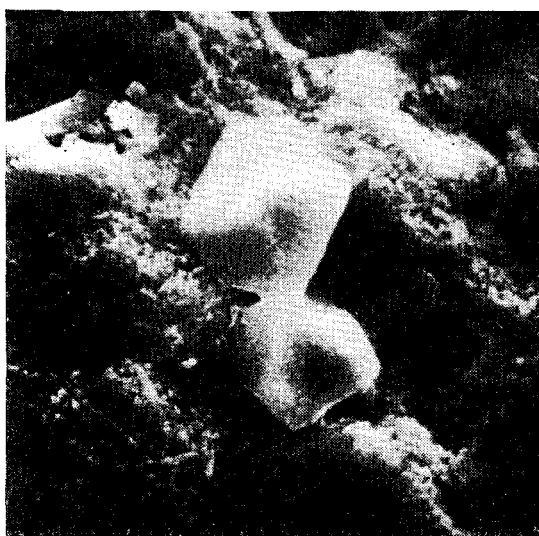


FIG. 25—SALT PARTICLES EMBEDDED IN TURBINE BLADE ( $\times 1400$ )

when five Sea King helicopters from the R.N. Air Station Culdrose took part in a search and rescue operation in the English Channel to aid the sinking M.V. *Merc Enterprise*. This operation was carried out in extreme conditions with winds gusting to 80 knots accompanied by very heavy breaking seas (FIG. 22). Lengthy periods were spent flying at low level over the sea. Considerable salt deposits were noticed accumulating on the aircraft reducing windscreen visibility. During the return, all the helicopters experienced varying degrees of power loss and some suffered intermittent engine stall to a very serious extent which eventually caused two forced landings. When the engines were inspected, heavy salt contamination was found in all intakes and compressors. The condition of one of these compressors, after strip, is shown in FIG. 23. This was a classic, if extreme, example of flight through sea mist rather than sea aerosol.

In the course of normal engine development, improvements in high temperature characteristics have been obtained by reducing chromium content to accommodate more of the high temperature strengthening elements. Usually a decrease in resistance to simple oxidation is not a critical factor in the durability of hot section parts, but in the marine environment, ingested sea-salt can accelerate corrosion attack to catastrophic levels of intensity in nickel- and cobalt-based superalloys. This type of corrosion attack is called 'hot corrosion'. The use of the term 'sulfidation' is also widespread if not specifically correct. FIG. 24 shows nozzle guide vanes removed from a small turboshaft engine which had been operated



in a marine atmosphere. This shows severe, but typical, 'warting' damage caused by hot corrosion.

Recent work at the NGTE by Restall to investigate the chemical and physical nature of hot corrosion (22) has indicated that graphite produced in the combustion chamber and dried sea-salt produce erosion and subsequent chemical degradation in the hot section. According to Restall, once graphite and salt particles are embedded in the blade surface, together or separately, they can induce rapid failure by virtue of their chemical activity with superalloys. FIG. 25 shows a scanning electron microscope (SEM) picture ( $\times 1400$ ) of a salt particle embedded in the pressure surface of a turbine blade.

## AIRBORNE PARTICLES DUE TO NATURAL CONDITIONS

### The Problem of Quantification

The development of the true 'all-weather' helicopter still awaits the solution of various technical problems before we can expect to see such a machine in service. The helicopter was a late entry into this field because the full significance of this restriction was not seen until the separate development of flight instruments and automatic stabilization equipment introduced an instrument meteorological conditions (IMC) capability. The retraction of strategic interests from hot climates back into Europe occurred about the same time; this created a positive incentive to modify existing helicopters for all-weather operation (23). Considerable practical experience has been gained by the A. & A.E.E. Boscombe Down in their attempts to achieve this (FIGS. 27 to 32 are from A. & A.E.E. trials) and, in parallel, R.A.E. Farnborough are investigating the more theoretical aspects to allow future designs to be built on a solid foundation.

If progress is measured in terms of hardware in service, then progress has been slow. The fundamental reason for this is that the incidence and nature of the meteorological conditions which can be expected are uncertain and are largely unexplored. Collection of statistical evidence in the past has been influenced by the advantages of altitude to fixed-wing operation, and has largely overlooked the helicopter's modest altitude band in the lower four figure region. Thus the design authority is faced with a task of designing with parameters that have not been properly established, and the clearance authority is faced with the task of testing hardware in conditions that are not necessarily those that operators are going to meet. This is a situation which can only cause multiplication of safety factors and produce disappointing releases. It is therefore quite clear that if practical solutions are going to be produced with an acceptable performance penalty and at an acceptable cost, one of the things which must be resolved is a quantification of the helicopter's natural environment in other than visual meteorological conditions (VMC).

### Ice

Clouds consist of very small drops of free water which may exist in the liquid state well below the normal freezing point. These super-cooled water droplets will form ice on any impacting surface which is maintained at a temperature below  $0^{\circ}\text{C}$ . The impact upsets the unstable state, and a return to the stable condition is made by forming a mixture of ice and water, the proportions depending on the degree of supercooling. Further heat transfer processes result in some or all of the remaining water freezing as it moves away from the point of impact.

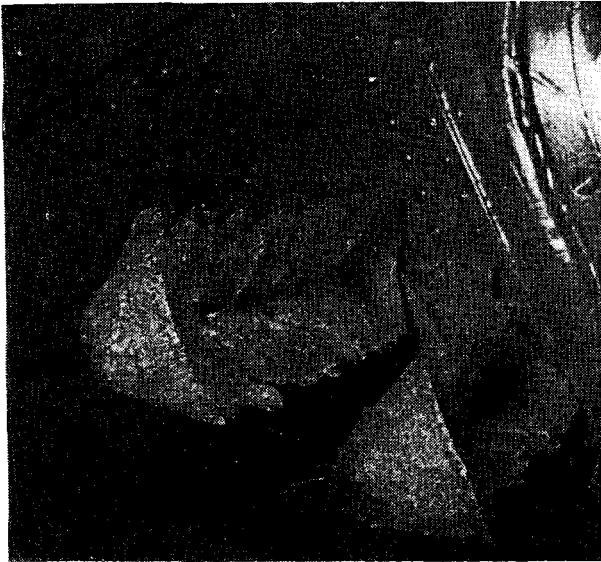


FIG. 26—CLEAR ICE ON AIRFRAME FITTING AFTER 31 MINUTES IN STRATUS CLOUD AT  $-1.5^{\circ}\text{C}$  AND 130 KTS

The ice potential of a cloud is a function of its liquid water content (LWC), usually expressed as grams of liquid per cubic metre of air excluding water in vapour form. The distribution of the LWC within a cloud depends on a variety of meteorological factors, and the result is that a cloud is not homogeneous in this respect either vertically or horizontally. Values collected by sampling aircraft tend to be the statistical means along their path through a cloud.

Water droplet size is expressed as the volume median diameter in microns. The size of the droplets affects the collection efficiency of a surface travelling

through a cloud, as the greater mass of the larger droplets will cause them to follow a flatter trajectory when the disturbance of a body is felt. Typical icing cloud droplet diameters are between  $10\mu$  and  $40\mu$  (23).

Icing cloud temperatures may vary from  $0^{\circ}\text{C}$  to  $-40^{\circ}\text{C}$ . Analysis has shown that the preponderance of ice occurs at temperatures warmer than  $-10^{\circ}\text{C}$ . Below  $-40^{\circ}\text{C}$  supercooled water droplets rarely exist and icing conditions will not be met. However, in the low altitude areas of interest to the helicopter such very low temperatures are not considered relevant.

The form which the ice adopts is influenced by the freezing fraction—the proportion of water which freezes instantaneously on impact with the surface. The free water remaining will be blown away from the point of impact freezing as it goes. At temperatures just below zero, a great deal of free



FIG. 27—CLEAR ICE ON UNDERCARRIAGE AFTER 60 MINUTES IN ICING CLOUD AT ZERO TO  $-1^{\circ}\text{C}$

water will exist, and the wandering path it takes before it finally freezes may give rise to the characteristic horned shape called clear or glaze ice (FIGS. 26 and 27). The additional and more positive kinetic force which is imparted to free water on a rotor blade raises some doubts as to whether this classic clear ice formation can be grown under these conditions.

At lower temperatures, the freezing fraction is higher and the immediate freezing of the droplets causes the ice to adopt a smoother profile. This is called rime ice.

### Icing Standards

The existing fixed-wing icing standards have been used over the past twenty years in the design of fixed-wing protection systems and have proved realistic (24). McNaughtan (25) has examined the basic U.S. and U.K. data on which these standards were based to see if they would be acceptable for helicopters operating in the low altitude range, where different conditions may be encountered which were statistically insignificant to the fixed-wing operating envelope. He concluded that, in the helicopter operating envelope, the standards defined for fixed-wing 'continuous maximum' conditions (24) accurately define the conditions encountered over long distances with some evidence indicating that water concentration reduces below 4000 feet. He also found good evidence that intermittent encounters with more severe conditions could occur over short distances (4 miles); this he put at twice the concentration appropriate to that temperature and altitude. The 'intermittent maximum' condition for fixed-wing aircraft (24) was ignored on the assumption that, as it referred to penetration of active cumulus cloud, it was not applicable to a helicopter. FIG. 33 gives these conclusions in graphical form.

### The Effect of Ice

Ice will tend to be collected only by forward facing surfaces of small frontal area. This is because the inertia of a water droplet of relatively small mass is easily overcome by the drag forces of the diverging streamlines due to an approaching blunt body. Thus ice is usually observed only on rotor blades, landing gear struts, aeri-als and other thin sections. Freezing rain (FIG. 32) produces droplets in the  $1000\mu$  range and will tend to coat all the forward-facing surfaces with ice, as the drag forces have little influence on

the inertia of these large particles.

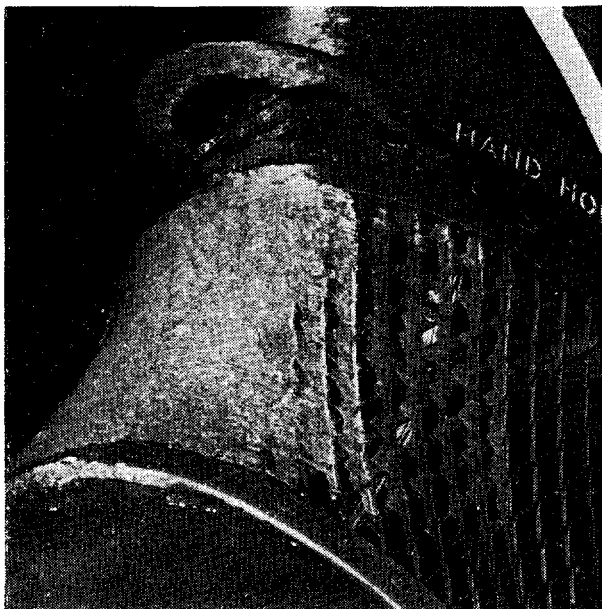


FIG. 28—64 MINUTES IN ICING CLOUD AT 1.4°C

Flight in icing conditions can create a variety of hazards for a helicopter, such as damage to engines, loss of vision, increase in airframe weight, blocking of cooling ducts (FIG. 28) and restriction of moving parts. All these are shared with fixed-wing aircraft and their effects can be contained by the application of established fixed-wing technology. As they do not constitute specific helicopter problem areas, they will not be discussed further. The major icing effect which the helicopter does not share is the effect that ice has on the rotor system.

This was a problem which was not fully recognized in the early part of the Ministry's helicopter anti-icing programme. The small amount of evidence that was available at that time gave promise of an adequate degree of 'self-shedding' from the rotors in a certain temperature band below  $0^{\circ}\text{C}$ , and the main effort was concentrated on correcting some unsatisfactory features in engine intake designs. As the test programme developed (limited by availability of the correct conditions to a few months each year), so the rotor problem was compounded by the wide variation in the effects of icing in what appeared to be very similar conditions. In many instances, extended flights of over an hour were achieved in what appeared to be light to moderate icing conditions, whereas on one occasion accumulations of ice on the rotor were such as to cause very rapid rise of engine torque which approached the permitted safety level in less than one minute necessitating rapid departure from the condition. FIGS. 29 and 30 show the main rotor blade ice pattern collected by two identical helicopters flying simultaneously in cloud 15 miles apart.

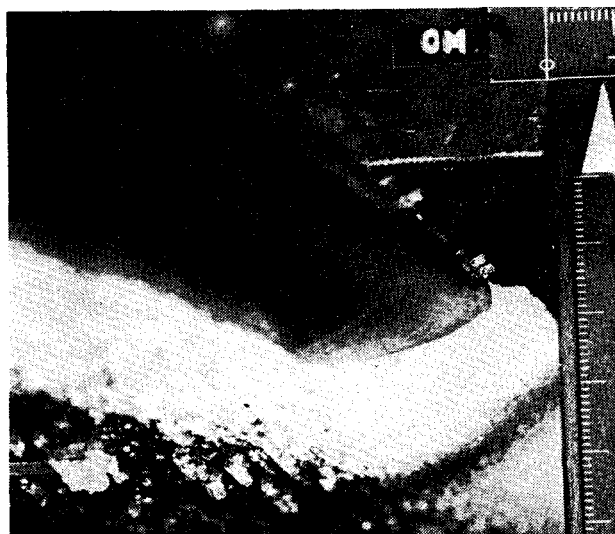


FIG. 29—21 MINUTES IN ICING CLOUD AT  $-5^{\circ}\text{C}$

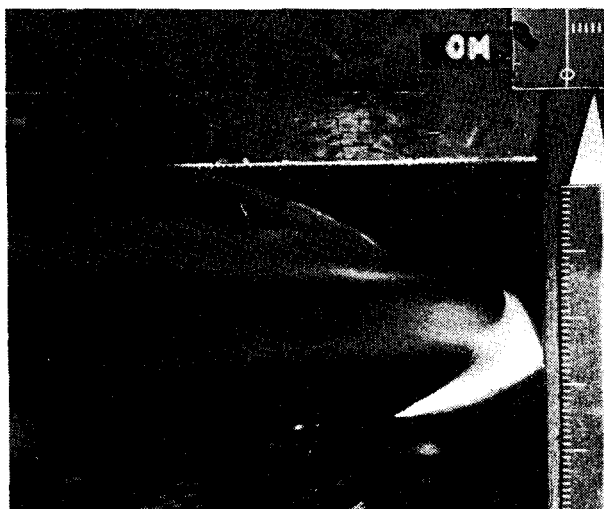


FIG. 30—50 MINUTES IN ICING CLOUD AT  $-6$  TO  $-8^{\circ}\text{C}$  (COLLECTED SIMULTANEOUSLY WITH THAT SHOWN IN FIG. 29 ON IDENTICAL HELICOPTERS FLYING 15 MILES APART)

This obviously supports McNaughtan's thesis on the probability of pockets of double the expected concentration existing in an otherwise normal layer type cloud (25).

Build-up of ice on the main rotors can cause:

- (a) premature blade stall and large changes in pitching moment, leading to increase in oscillating torsional loads with the possibility of fatigue damage to the control mechanism;
- (b) vibration due to asymmetric loading causing fatigue damage in rotor system and other related parts of the airframe structure;
- (c) alteration to the aerodynamic characteristics, leading to torque rises to maintain flight, together with a loss in potential autorotative rev/min.

The effect of premature blade stall and vibration can be reduced by restricting forward speed whilst in a potential icing condition (defined as the presence of cloud, fog, or mist in the temperature range  $0^{\circ}\text{C}$  to  $-30^{\circ}\text{C}$ ). This is reflected in some current releases which limit speed to  $V_{\text{max}} - 10$  knots in potential icing conditions, with a further reduction to  $V_{\text{max}} - 25$  knots if ice is seen to form. This also has

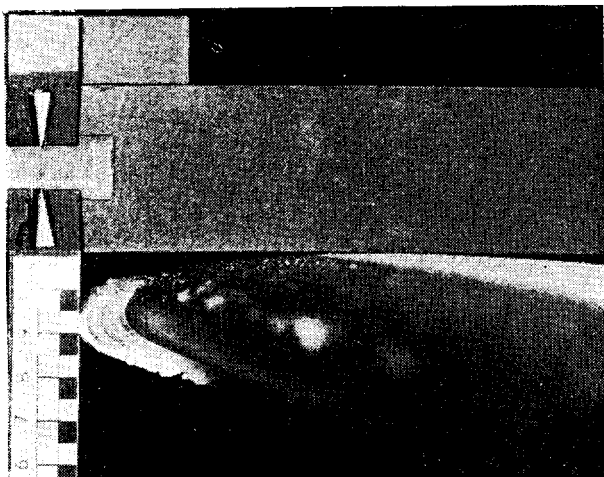


FIG. 31—47 MINUTES HOVER AND AIR TAXI IN FREEZING FOG, 200m VISIBILITY

form of reduction in the minimum pitch setting is required to keep the autorotative rev/min up to acceptable limits. In addition, even though successful autorotation may be possible (albeit at an increased rate of descent) severe icing would create difficulties during recovery, when the rotor will require to operate at considerably greater angles of attack. These findings were those which were expected and confirmed the need to keep the engines going, with a necessary reserve of torque.

the bonus of reducing the torque requirement. The risk of premature blade stall can also be reduced by descent to a lower altitude.

A theoretical study into the effects of rotor ice accretion on the steady-state autorotative performance has recently been completed (26). This used a rotor performance computer programme in conjunction with postulated modifications to the aerofoil data to represent iced rotors. Within the limitation of such a study, the main conclusions were that when significant ice accretion has occurred some

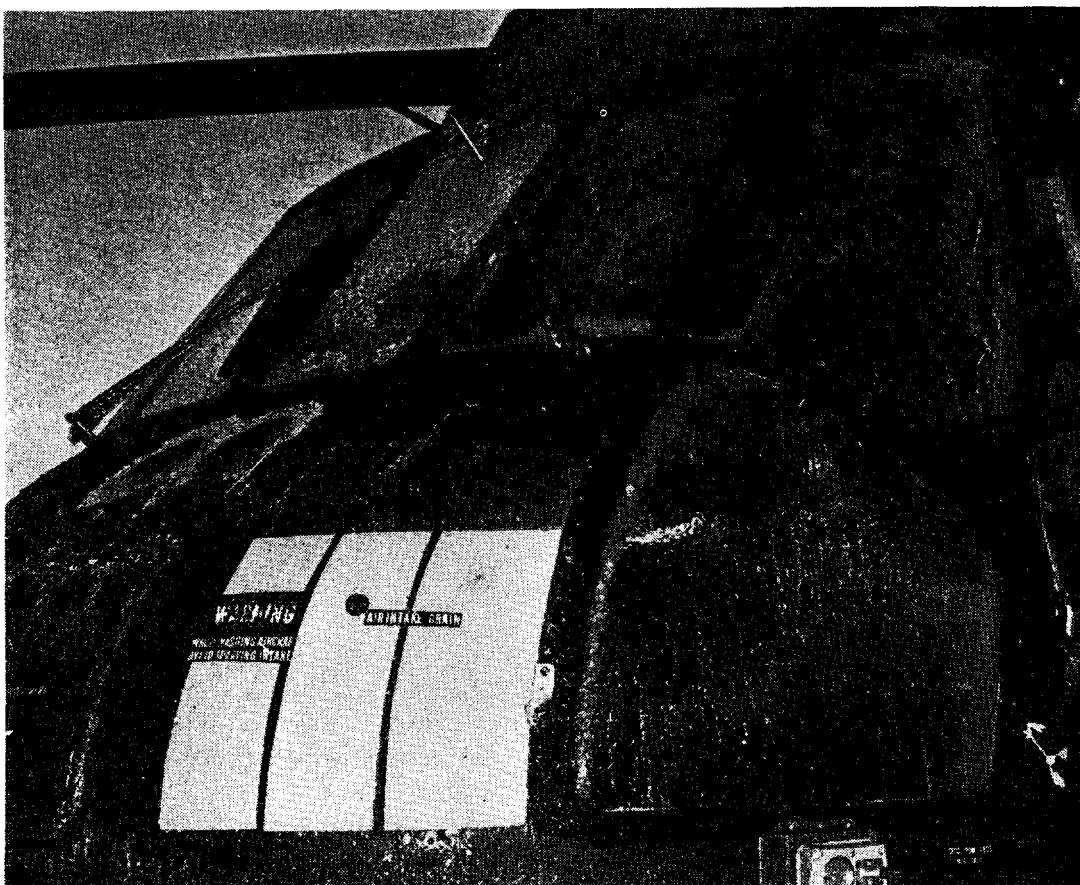


FIG. 32—16 MINUTES IN MODERATE FREEZING RAIN AT 0°C

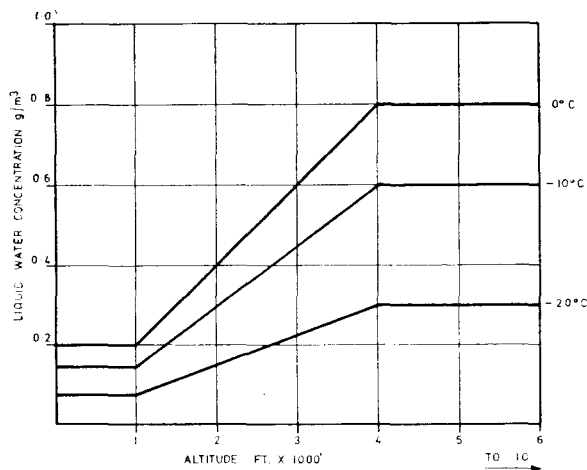


FIG. 33—CONTINUOUS MAXIMUM CONDITIONS FOR HELICOPTERS PROPOSED BY MCNAUGHTAN (25) 0 TO 10 000 FT.  $20\mu$  VOLUME MEDIAN DIAMETER—WITHIN THIS ENVELOPE ASSUME A PROBABILITY OF INTERMITTENT ENCOUNTERS EVERY 50 MILES, 4 MILES EXTENT, OF TWICE CONTINUOUS VALUE

Considerable effort is now being expended in investigating the value of various schemes for providing rotor protection against ice. Whilst this is essential, it must also fit into an advance against the problem on a broad front. For a standard fleet fit of icing equipment to be cost effective, it must only provide the minimum protection required. And before the minimum degree of protection can be assessed, it is also necessary to have:

- (a) A fuller understanding of the physics and distribution of natural icing, particularly in the lower levels.
- (b) A more complete understanding of the effects of ice on rotor behaviour.
- (c) A reliable and accurate instrument to indicate the severity of the local icing condition.
- (d) An accurate method of full-scale testing.

The possession of these factors will allow the total problem to be seen with a greater depth of perspective. It might even allow some limited operational envelope to be described in which flight in modest icing conditions could be authorized without formal rotor protection at an acceptable risk. The economics of such a practical solution appear attractive enough to justify the necessary research effort.

## Snow

Snow covers permanently or temporarily about 23 per cent. of the earth's surface. It takes the form of crystals of white ice, apparently opaque, generally in flakes of light feathery structure. Small flakes (up to 4 or 5 mm diameter) often show a six-rayed star-like structure. Larger flakes usually consist of aggregates of such crystals, the general structure being no longer perceptible. Large flakes (diameters of up to 25 mm) are usually found only when the temperature is near  $0^{\circ}\text{C}$ . At low temperatures the snow may fall as a fine dry powder.

Snow is usually forecast when the surface temperature is below about  $+4^{\circ}\text{C}$  in situations which would otherwise give rain. The exact critical temperature depends on circumstances and there is no hard-and-fast rule (27). For design purposes, quantification of airborne concentration is an obvious requirement. Hardy (28) has produced data on the probability of the occurrence of 'equivalent rainfall' for various stations in the U.K. His analysis considered rainfall rate statistics for a temperature band wherein it is known that a large proportion of the precipitation will have fallen as rain. It is then argued that this represents an upper envelope for snowfall rates. Using Hardy's assumptions, McNaughtan (29) further converted Hardy's data into an approximate probability of occurrence of snow concentration in the U.K. with the following results:

<i>Airborne Concentration</i>	<i>Probability</i>
0.5 g/m <sup>3</sup>	1 in 10 <sup>3</sup> hours
1.0 g/m <sup>3</sup>	1 in 10 <sup>4</sup> hours
1.5 g/m <sup>3</sup>	1 in 10 <sup>5</sup> hours
2.0 g/m <sup>3</sup>	1 in 10 <sup>6</sup> hours

Using this technique, an extension to world-wide conditions must also be possible, allowing a design value for snow concentration to be obtained by selection of a design probability. This analysis includes sleet (rain and snow falling together) implicitly, as mixed precipitation most often occurs between 0 and 2.5°C.

### **The Effect of Snow**

There is no evidence that snow in isolation causes any significant change in rotor aerodynamics. Any hazard due to flight through snow comes from the danger of engine damage or flame-out. Although this is a danger common to fixed-wing aircraft in the same conditions, it is discussed here because experience has shown that some helicopter engine intakes with particle separation features react unfavourably in a snow encounter. A significant complication is the fact that some important physical changes occur in snow with variation of temperature. Low temperature snow tends to small hard dry particles which rebound from a cold surface. Snow at higher temperatures tends to large wet particles which may stick on collision. This means that the behaviour of snow passing through any system of ducting will be, to a large degree, a function of its temperature. Snow at near freezing point will tend to stick at points where any re-direction of the airflow encourages momentum separation. This may cause build up with the danger of ingestion of relatively large masses of packed snow and slush. The application of sufficient heat to any collection areas (which may already be heated for anti-icing purposes) is a way of overcoming the problem, except that this may now cause low temperature snow, previously no problem, to start to stick and build up. Thus an engine intake with any significant bends has conflicting design requirements to cope with snow over, say, a 15°C temperature band.

A classic example of this was the problem of the Proteus engine in the early days of the Britannia aircraft. In the course of proving flights over Africa in 1955-6, flame-outs were experienced on a number of occasions after flight through cloud. Investigation showed that pockets of cold dry ice crystals were collecting in the reverse bend where the surface was warmed for anti-icing purposes. The initial solution was to insulate the warm catchment areas and to keep all ducting 'cold and smooth'. The trouble started again in 1957 and this time it was due to wet snow, just below freezing, building up on the now cold bend. The problem was eventually solved by other means (23).

Hovering over snow will induce the type of recirculation illustrated in FIG. 3. It can be seen that, with a certain relative wind on the nose, engine intakes can be expected to enter a very high area of concentration and ingest snow at a much higher rate than that to be expected in flight through falling snow, and this may restrict the time of hover. It is sometimes used to observe the performance of engine intakes in snow conditions, but it suffers from the disadvantage of an additional down-flow component at intake entry which



does not make this test fully representative of forward flight although it is a useful development technique.

Once snow has been deposited on the ground, refreezing of the meltwater and strong winds may lead to the formation of a hard surface crust. Landing on crusted snow causes little or no recirculation.

In operating areas, snow which has been impacted by tracks or feet and then refrozen has been found to be a very real hazard in helicopters with low engine intakes. The record shows a high number of engines damaged by impacted ground ice that has been disturbed by the downwash and then ingested.

### **Mixed Conditions**

Ice crystals and supercooled water droplets can co-exist in a cloud during glaciation or when snow falls into a supercooled water cloud. It is generally true that heavy snow and supercooled water do not co-exist (28). Mixed conditions met during icing trials provided some evidence that they may lead to an increase in icing severity depending on the ambient temperature and liquid to solid water ratio, although the exact mechanism is not fully understood. Particular problems have been experienced in thermally anti-iced regions where the presence of ice crystals upsets the heat transfer balance designed to deal only with supercooled water droplets. The degree of liquid to solid water ratio is very difficult to forecast as in theory any ratio may exist. Design standards are about to be proposed which specify  $0.2\text{g}/\text{m}^3$  LWC water  $0.8\text{g}/\text{m}^3$  ice crystal.

### **Freezing Rain**

Precipitation in this form requires a sub-zero layer underlying warmer air (temperature inversion). Falling snow melts whilst traversing the warm layer and subsequently becomes supercooled. The resulting drops freeze on impact producing a coating of clear ice. Because of the much larger drop size, there is only a negligible tendency for the drops to be deflected, and this results in ice forming on forward-facing parts of the helicopter which otherwise remain free of ice in an icing cloud (FIG. 32). According to NACA Technical Note 1855, freezing rain is characterized by droplet sizes of about  $1000\mu$ , temperatures of  $0^\circ\text{C}$  to  $-5^\circ\text{C}$ , altitudes 0 to 5000 ft and LWC of  $0.15\text{g}/\text{m}^3$ , with a horizontal extent of as much as 100 miles (23). Freezing rain can present a helicopter with a very serious situation as there is usually no option of climbing out of the condition. Fortunately, high rates of freezing rain are rare and short lived because the condition tends to be self cancelling; the melting layer is cooled and the freezing layer is warmed by the reverse process. According to Hardy (28), the limited evidence available suggests that the probabilities of high rates of freezing rain may be rather less than 1 per cent. of those for snow. The only practical solution to the freezing-rain problem may be confined to accurate forecasting followed by avoidance.

### **Rain and Hail**

This is basically an erosion issue usually associated with high-speed flight. The effect on a helicopter will in general be limited to the outboard sections of rotor-blade leading edges and, as already discussed, tested solutions are available which are now compatible with the anti-erosion measures required for protection against solid particles. Thus rain and hail are not considered to be a special environmental hazard for the helicopter, notwithstanding the potential damage that tropical rain may cause to polyurethane protection of rotor blade leading edges mentioned previously.

## Industrial Pollution

The commonest and most widespread particulate pollution is emitted by industrial and domestic chimneys, and therefore atmospheric pollution is usually associated with combustion of fossil fuel. (The chemical industry also produces other forms of particulate pollution, but not widespread enough to be considered a problem.) The smoke produced by the combustion of fuel consists mainly of carbon, tar, and ash. Ash tends to be deposited first, and this means that suspended impurities are mainly carbon and tar (30).

Compressor fouling due to pollution was first noticed on some development engines running in test cells in industrial areas, requiring compressor washing to restore performance. This is essentially a low-altitude problem and one which has been experienced in service, in particular by R.A.F. helicopters flying in the Ruhr Valley and Army helicopters flying in Hong Kong. It must also apply to naval helicopters after prolonged operation in funnel gases. Although compressor washing with a suitable solvent is an acceptable solution, this problem may also affect the operation of particle separation systems by depositing sticky substances in air passages designed to encourage the passage of dust. Dust separator designs, therefore, may also need to consider the requirement for removing industrial deposits.

## Visibility in Cloud and Precipitation

An immediate problem facing operators is how far to let helicopters venture into conditions, the nature and effects of which are not properly understood. At this moment, we rely almost entirely on an accurate forecast and some primitive instrumentation to define the point at which the flight must be revised or terminated. This is very restrictive. It is felt that some immediate advance might be made if the man flying the helicopter was called upon to exercise his judgement of the ambient conditions and act accordingly. This is a requirement as old as flying itself. It is known that a relationship exists between particle concentration in the atmosphere and the visibility through it, and it is necessary to establish what this relationship is as a simple aid to airmanship. Admittedly this method would be difficult to use at sea and impossible to use at night, or when flying in cloud.

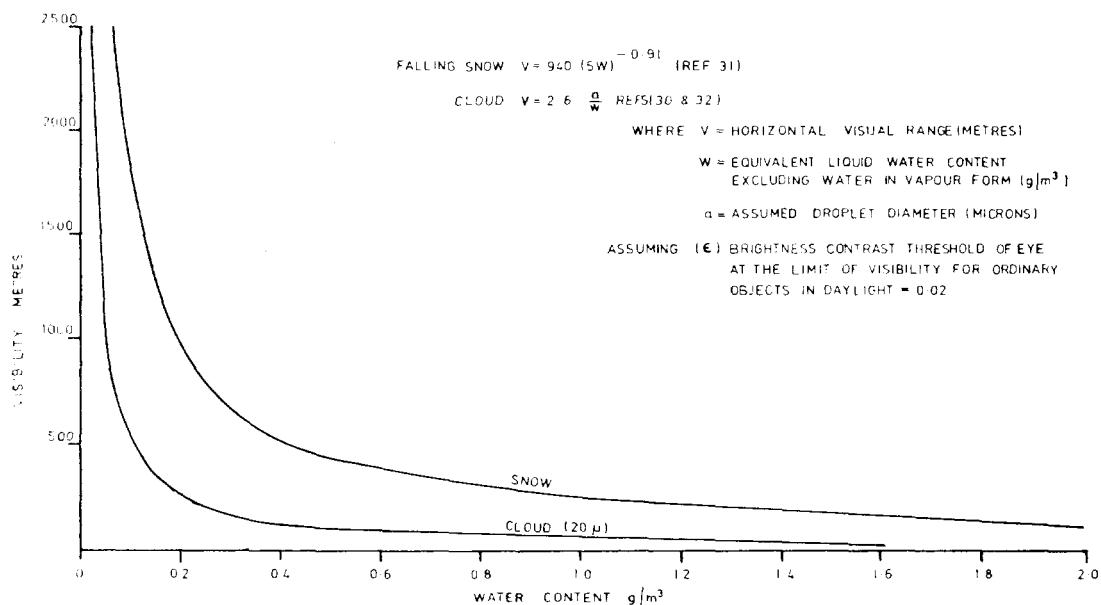


FIG. 34—EXAMPLES OF CALCULATED HORIZONTAL VISUAL RANGES IN SNOW AND CLOUD

Green and Lane (30) have developed an equation for visual range in fog, which also appears applicable to cloud. A similar analysis has been carried out by Middleton (32). Poljakova and Tretjakov (31), from work in the U.S.S.R., have developed formulae for the visibility to be expected in falling snow. The equations are illustrated in FIG. 34.

As an example, these results suggest that if a particular installation was considered to have an unacceptable threshold of risk at  $0.2\text{g/m}^3$  LWC, it would relate to an approximate visibility of 1000 metres in falling snow and 250 metres in cloud. This is, of course, before application of safety factors and agreement of the constants to be used in the equations.

The use of such simple visibility criteria, in spite of obvious limitations, is probably the only common ground on which the designer and user can meet at this time. In due course, it is hoped to have helicopters which may confidently be expected to deal with these conditions and with any limitations related to reliable cockpit instruments; but, in the present state of the art, it is necessary to take what is available and visibility criteria seem a good starting point. Apart from giving each pilot some yardstick to help him appreciate the situation, it could also provide the bonus of a feedback of information of actual service experience helping the understanding of the total problem.

## CONCLUSIONS

This article is an attempt by a user to look at the nature and scale of the special environmental problems facing the practical helicopter designer. This was prompted by a feeling that some of the existing design criteria have been over-influenced by the special environmental problems which have faced fixed-wing aircraft for many years.

From this viewpoint the main conclusions are clear. Far more knowledge is necessary about the conditions in which a helicopter is expected to operate, particularly in IMC. Furthermore, the total environmental requirement needs specifying in a way which precludes a piecemeal approach, and which acknowledges the incompatibility that individual solutions may have with each other.

It is unreasonable to expect engineered solutions to these environmental problems until the manufacturer is contractually obliged to produce them. A realistic and enforceable contract cannot be established unless it can be based on an exact specification of the requirement. At the moment, our standard Design Requirements (33) include very little of what has been discussed in this article, and therefore it must be accepted that in many respects the next generation of helicopters will be as vulnerable as the current generation. In particular, this applies to damage from rotor generated dust and sand. The only requirement to cover this in AvP 970 (33) is the statement 'There shall be no risk of sand or dust entering any working parts unless the parts are designed to operate satisfactorily under these conditions'. The author pointed out this problem in an article in the *Journal of Naval Engineering* in 1960 (7), and since then we have had the severe examples of Wessex 1 and 5 operation in sandy and dusty conditions, followed by the massive and well documented U.S. helicopter experience in Viet Nam.

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