SOME ENVIRONMENTAL PARAMETERS ESSENTIAL

FOR PRACTICAL HELICOPTER DESIGN

Commander M.F. Simpson Royal Navy

Directorate of Helicopter Projects

Ministry of Defence

Paper No. 27

2. This paper expresses the opinions of the Author, and does not necessarily represent the official view of the Ministry of Defence.

Room 811
Procurement Executive
St. Giles Court.

August 1975.

<u>SOME ENVIRONMENTAL PARAMETERS ESSENTIAL TO PRACTICAL HELICOPTER DESIGN</u>

1. The Special Case of the Helicopter.

1.1 Introduction.
1.2 The Helicopter Environment.

2. Airborne Particles due to Rotor Downwash.

2.1 Rotor Recirculation in Ground Effect.
2.2 The Effect of Recirculation.
2.3 Sand and Dust.
2.4 The Nature of Solid Particle Erosion.
2.5 Rotor Blade Erosion.
2.6 Engine Erosion.
2.7 Surface Debris.
2.8 Airborne Salt.
2.9 The Effect of Airborne Salt.

3. Airborne Particles due to Natural Conditions.

3.1 The Problem of Quantification.
3.2 Ice.
3.3 Icing Standards.
3.4 The Effect of Ice.
3.5 Snow.
3.6 The Effect of Snow.
3.7 Mixed Conditions.
3.8 Freezing Rain.
3.9 Rain and Hail.
3.10 Industrial Pollution.
3.11 Visibility in Cloud and Precipitation.

4. Conclusions.

1. THE SPECIAL CASE OF THE HELICOPTER

1.1 INTRODUCTION

This paper is an attempt to identify the severe environments that are a direct 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 paper is not intended to be a comprehensive effort to establish general guidelines; its object is simply to illuminate the problem.

1.2 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.

2. AIRBORNE PARTICLES DUE TO ROTOR DOWNWASH

2.1 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 3-5 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 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 energise 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).

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, (one micron (μ) = 10^{-3}mm or 0.00004" in diameter)(6) 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 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).

2.2 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, and difficulty in achieving effective operational concealment.

Figures 8, 9 and 10 show examples of clouds raised whilst landing or hovering over different surfaces. Various flying techniques have been established and are practiced to minimise the effect of the cloud raised during landing and take off, but the problem still exists, particularly when more than one helicopter 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.

2.3 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, particularly when the surface layer has been disturbed. In these areas the soil exhibits a greater tendency to stick together on the surface, giving a 'pavement' which in general, varies between ¼" and 2" 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 helicopter 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), occuring 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, an SG 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.

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

2.4 THE NATURE OF SOLID PARTICLE EROSION

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

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

I.E. 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.

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 Figure 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 ϵ is for normal impact against steel at 420 ft/sec, and ηq 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 stabilised 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.

2.5 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 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 effects 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 in paragraph 2.4. 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. 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, and 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 Figures 16 and 17. This was a problem 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).

2.6 ENGINE EROSION

The first generation of helicopter engines was based on a gas turbine 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 recognised 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 - 20% of the normal time between overhaul (TBO) period. In the U.S.A., this stimulated immediate development and re-design 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 engine erosion problem is alteration of the compressor aero-foils. 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 saying that the particles tend to be centrifuged out-wards, concentrating damage at the blade tips and stator roots. Besides jeopardising 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 ϵ appearing constant for any realistic dust concentration up to 13 Mg/ft^3. 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).

Bianchini and Koschman carried out dust erosion tests of a T-63, using selected sizes of coarse Arizonia Road Dust. They found engine power decreased almost linearily with total dust ingested, apparently indep-endent of dust concentration (see also Para. 2.4.d). Up to 10μ had little effect, 0-20μ was not severe, and the 0-80μ and 0-200μ tests were both severe, but not noticeably different (18). This supports the NGTE 'plateau' observations (Para. 2.4.c.).

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.

2.7 SURFACE DEBRIS

This covers material which has a large surface area in relation to its mass, which allows it to be energised by the rotor recirculation system. Damage to engines has been caused by natural and cultivated vegetation (Figures 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.

2.8 AIRBORNE SALT

For convenience, this section discusses the presence of sea salt due to both rotor induced downwash and 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 within 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, and 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 be said to consist of particles considerably larger than 25μ. Mists generated by a ship's bow will depend on sea state, ships 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 0.1μ to 20μ, with the peak in the mass size distribution increasing from about 1.5μ at wind force 1, to 6μ at wind force 7 (Beaufort Scale). Tests at Key West showed an aerosol concentration between 0.0016 to 0.0275 parts per million by weight (PPM), with an average of 0.0113 PPM. Figure 21 shows the relationship between average mass medium size against wind velocity (20).

The critical humidity below which salt particles are dry is 75-76%. Relative humidity in the 30 foot layer does not normally drop below 79%, 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% (19).

Some U.S.N. data, sampled from a helicopter 10 to 30 feet above the sea, found particles of 150μ to 500μ with a 50% probability diameter in the range 20μ to 90μ, 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. Reference to paragraph 2.1 shows how the surface wind speed under the hover of a typical anti-submarine helicopter will be in the region of 45 knots (Force 9) which can explain the U.S.N. results. Figure 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 Figure 3 was derived. This shows that for the particular configuration shown, hovering into a 10-knot wind is the worst conditions for the engines.

2.9 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. The effect of this exposure can cause :-

a) low temperature or aqueous corrosion in the airframe, and in the compressor section of the engine.

b) Salt deposit on the transparancies.

c) Salt deposits on the rotor blades.

d) Salt deposits in the compressor.

e) High temperature corrosion or sulfidation of the engine hot section.

Low temperature corrosion of aircraft in a marine environment is a problem which has received considerable attention in the Royal Navy. It was both recognised 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.

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 not only occurs 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 discussed in paragraph 2.5 (14). An example of salt deposits on a main rotor blade after low level flight over rough sea is shown in Figure 21 (described et sec).

In January 1964, 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 MV 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. 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 Figure 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. Figure 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. Figure 25 shows a scanning electron microscope (SEM) picture (X1400), of a salt particle embedded in the pressure surface of a turbine blade.

3. AIRBORNE PARTICLES DUE TO NATURAL CONDITIONS

3.1 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 stabilisation equipment introduced an instrument meteorological conditions (IMC) capability. The retraction of strategic interests from hot climates back into Europe occurred about the same time, which created a positive incentive to modify existing helicopters for all weather operation (23). Considerable practical experience has been gained by the A&AEE Boscombe Down in their attempts to achieve this (Figures 27 to 32 are from A&AEE trials), and in parallel, RAE 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 which have not been properly established, and the clearance authority of testing hardware in conditions which 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).

3.2 ICE

Clouds consist of very small drops of free water, which may exist in the liquid state well below the normal freezing point. These supercooled water droplets will form ice on any impacting surface. 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.
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 mean along their path through a cloud.

Water droplet size is expressed as the volume mean diameter in microns. The size of the droplets effects 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 10μ and 40μ (23).

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

The form which the ice adopts is determined by the freezing fraction, which is 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 water will exist, and the wandering path it takes before it finally freezes may give rise to the characteristic horned shape, called clear ice (Figures 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.

3.3 ICING STANDARDS

The existing fixed wing icing standards have been used over the past 20 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), which 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. Figure 33 gives these conclusions in graphical form.

3.4 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 we usually observe ice only on rotor blades, landing gear struts, aerials and other thin sections. (Freezing rain (Fig.32) (para.3.8) produces droplets in the 1000μ range, will tend to coat the all forward facing surfaces with ice, as the drag forces have little influence on the inertia of these large particles).

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 recognised 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, 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. Figures 29 and 30 show the main rotor blade ice pattern collected by two identical helicopters flying simultaneously in cloud 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 clouds (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 assymetric 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 RPM.

The effect of premature blade stall and vibration can be reduced by restricting forward speed whilst in a potential icing condition. This is reflected in some current releases which limit speed to Vmax - 10 knots in potential icing conditions, with a further reduction to Vmax - 25 knots if ice is seen to form. This also has the bonus of reducing the torque requirement.

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 form of reduction in the minimum pitch setting is required to keep the autorotative RPM up to acceptable limits. In addition, even though successful autorotation may be possible (albeit at an increase 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.

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 we also need :-

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 authorised without formal rotor protection, at an acceptable risk. The economics of such a practical solution appear attractive enough to justify the necessary research effort.

3.5 SNOW

Snow covers permanently or temporarily about 23% 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°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°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 :-

Airborne Concentration g/m^3	Probability
0.5	1 in 10^3 hours
1.0	1 in 10^4 hours
1.5	1 in 10^5 hours
2.0	1 in 10^6 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) implicity, as mixed precipitation most often occurs between 0 and 2.5°C.

3.6 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 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 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 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, over 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 1955/56, 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 Figure 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, which has been disturbed by the down-wash and then ingested. (Para.2.7).

3.7 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 have been met during icing trials, which 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 o.2g/m^3 LWC water 0.8g/m^3 ice crystal.

3.8 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 (Figure 32). According to NACA Technical Note 1855, freezing rain is characterised by droplet sizes of about 1000μ, temperatures of $0^{\circ}C$ to $-5^{\circ}C$, altitudes 0 to 5000ft and LWC of $0.15 gm/m^3$, with an 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% of those for snow. The only practical solution to the freezing rain problem may be confined to accurate forecasting, followed by avoidence.

3.9 RAIN AND HAIL

This is basically an erosion issue, one 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 discussed in paragraph 2.5, 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.

3.10 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, which means 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 RAF helicopters flying in the Rhur Valley, and Army helicopters flying in Hong Kong. Although compressor washing with a suitable solvent is an acceptable solution, this problem may also effect 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.

3.11 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. We know that a relationship exists between particle concentration in the atmosphere and the visibility though it, and we need 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.

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 Figure 34.

As an example, these results suggest that if a particular installation was considered to have an unacceptable threshold of risk at $0.2 gm/m^3$ 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, we hope to have helicopters which we may confidently expect to deal with these conditions, with any limitations related to reliable cockpit instruments, but in the present state-of-the-art, we must take what we can get, and visibility criteria seems 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, which must help our understanding of the total problem.

4. CONCLUSIONS

This paper is an attempt by a user to look at the nature and scale of the special environmental problems facing the practical helicopter. This was prompted by a feeling that some of the existing design criteria has 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. We need to know far more 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.

REFERENCES

1. A.Wilson and W.E.R. Thain. Trials of Momentum Particle Sand Separator Door. A&AEE Boscombe Down Report (1967).

2. M.P. Cox. Trial on Momentum Separation Nose Door - Sand Sampling Testing. Bristol Siddeley Engines Report MR17 (1967).

3. E.A. Fradenburg. Flow Field Measurements for a Hovering Rotor Near the Ground. Paper at American Helicopter Society Fifth Annual Western Forum (1958).

4. M.M. George, A.A. Perlmutter and L. Butler. Editors. Downwash Impingement Criteria for VTOL Aircraft. Dynasciences Report No. DCR-139 (1964).

5. S.J. Rodgers. Evaluation of the Dust Cloud Generated by Helicopter Rotor Blade Downwash. Proceedings of the 7th Annual National Conference on the Environmental Effects on Aircraft and Propulsion System (1967).

6. P. Drinker and T. Hatch. Industrial Dust - McGraw-Hill (1954).

7. M.F. Simpson. Maintenance of an Independent Helicopter Force. Journal of Naval Engineering VOL 12 No.3 (1960).

8. H.C. Schafer. An Insight into the Mechanics of the Sand and Dirt Problem. Proceedings of the 8th Annual National Conference on the Environmental Effects on Aircraft and Propulsion Systems (1968).

9. J.E. Goodwin, Miss W. Sage, G.P. Tilly. Study of Erosion by Solid Particles. Proceedings of Institution of Mechanical Engineers VOL 184, Part 1. No. 15 (1969-70).

10. H.J. Mackay. Military Vehicles and Experimental Establishment Ministry of Defence. Private Communication (1975).

11. G.P. Tilly. A Two Stage Mechanism of Ductile Erosion. Wear 23 (1973).

12. G.P. Tilly. Sand Erosion of Metals and Plastics: A Brief Review. Wear 14 (1969)

13. P. Brotherhood. Some Aerodynamic Measurements in Helicopter Flight Research. RAE Technical Memo-Structures 859 (1975).

14. K.T. McKenzie. Deputy Chief Designer (2) Westland Helicopters Limited. Private Communication (1975).

15. A.A. Fyall, R.B. King, R.N.C. Strain. Rain Erosion Aspects of Aircraft and Guided Missiles. Journal of the Royal Aeronautical Society. July (1962).

16. J.R. Lee. Chief Materials Engineer Westland Helicopters Limited. Private Communication (1975).

17. J.E. Montgomery and J.M. Clark jun. Dust Erosion Parameters for a Gas Turbine. Society of Automotive Engineers Summer Meeting, Preprint 538A (1962).

18. G.V. Bianchini and R.B. Koschman. T-63 Engine Sand and Dust Tolerance. Proceedings of the 6th Annual National Conference on Environmental Effects on Aircraft and Propulsion Systems (1966).

19. Miss E.J. McNair. Directorate of Research (Ships): Ministry of Defence. Private Communication to NAML (1965).

20. J.E. Bullion and M.E. Dell. Evaluation of the Corrosion Resistant Properties of an All-Titanium Compressor on a T-64 Engine in a Salt Laden Air Environment. Proceedings of the 6th Annual National Conference on Environmental Effects on Aircraft and Propulsion Systems (1966).

21. T.F. Stirgwolt. Salt Water Ingestion by Gas Turbine Engines. Proceedings of the Conference on Environmental Effects on Aircraft Propulsion (1961).

22. J.E. Restall. Influence of Salt and Carbon Particles on the Behaviour of Hot Superalloy Components in Gas Turbine Engines. Unpublished NGTE Report (1975).

23. M.F. Simpson. Requirements for the Operation of Naval Helicopters in Icing Conditions. Director General, Aircraft (Naval) Report (1969).

24. AvP970 Design Requirements for Service Aircraft. Fixed Wing Icing Severity Standards Volume 1, Chapter 714.

25. I.I. McNaughtan. Definition of Icing Standards for Helicopters. Unpublished RAE Work (1973).

26. D.R. Shepherd and T.R. Stevens. A Theoretical Study into some of the Effects of Rotor Ice Accretion on the Auto-rotation and Engine Off Landing Performance of Helicopters. Westland Helicopters Limited.Report Aero Tech Note /GEN/011 March (1975).

27. A.F. Crossley and Others: Handbook of Aviation Meteorology. Meteorological Office HMSO (1971).

28. R.N. Hardy. Rates of Fall of Snow, Mixed Precipitation, and Freezing Rain. Meteorological Office Investigations Division Technical Note No. 9 (1974)

29. I.I. McNaughtan. Snow Concentration in the Lower Atmosphere. Unpublished RAE Work (1974).

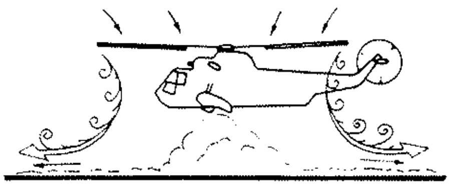
30. H.L. Green and W.R. Lane. Particulate Clouds. SPON, LONDON (1957).

31. E.A. Poljakova and V.D. Tret'jakov. Visibility in Falling Snow. Glav. Geof. Obs,T.Leningrad (1960)

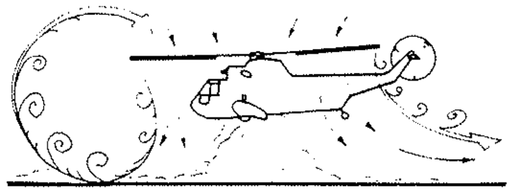
32. W.E.K. Middleton. Vision Through the Atmosphere. University of Toronto Press (1952).

FIG 1 SCOUT NEAR KUCHING, BORNEO.

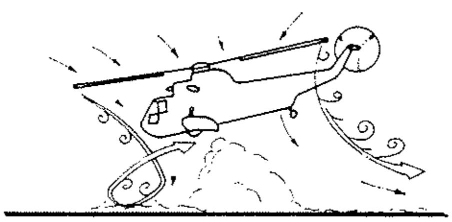
FIG 2 WESSEX HOVERING IN SAND



NO WIND



9 KNOTS WIND



20 KNOTS WIND

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

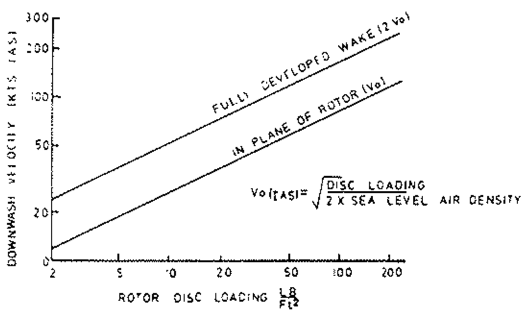


FIG 4 DOWNWASH VELOCITIES ACCORDING TO SIMPLE MOMENTUM THEORY FOR ROTORS OUT OF GROUND EFFECT

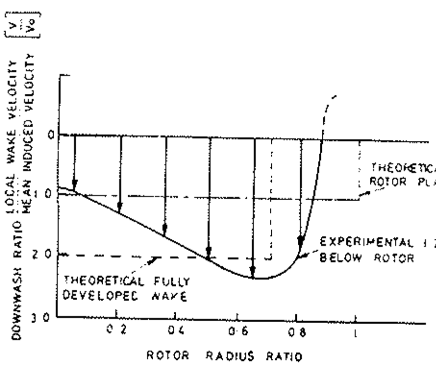


FIG 5 COMPARISON BETWEEN THEORETICAL AND EXPERIMENTAL MODEL DOWNWASH VELOCITIES FOR ROTOR OUT OF GROUND EFFECT

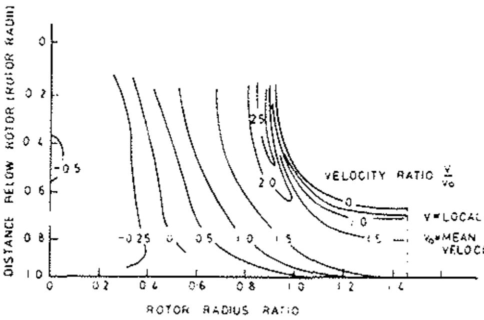


FIG. 6 VELOCITY CONTOUR MAP FOR A ROTOR 1 0 RADIUS ABOVE GROUND

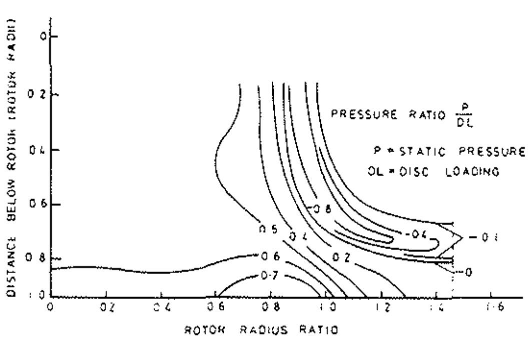


FIG. 7 STATIC PRESSURF CONTOUR MAP FOR ROTOR 1 0 RADIUS ABOVE GROUND.

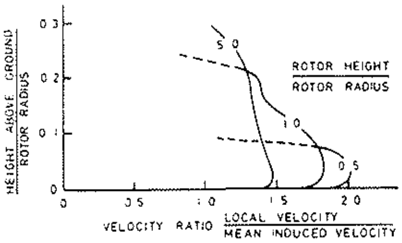


FIG 8 VELOCITY PROFILES ALONG GROUND MEASURED AT A DISTANCE OF 1½ ROTOR RADII FROM ROTOR CENTRE LINE

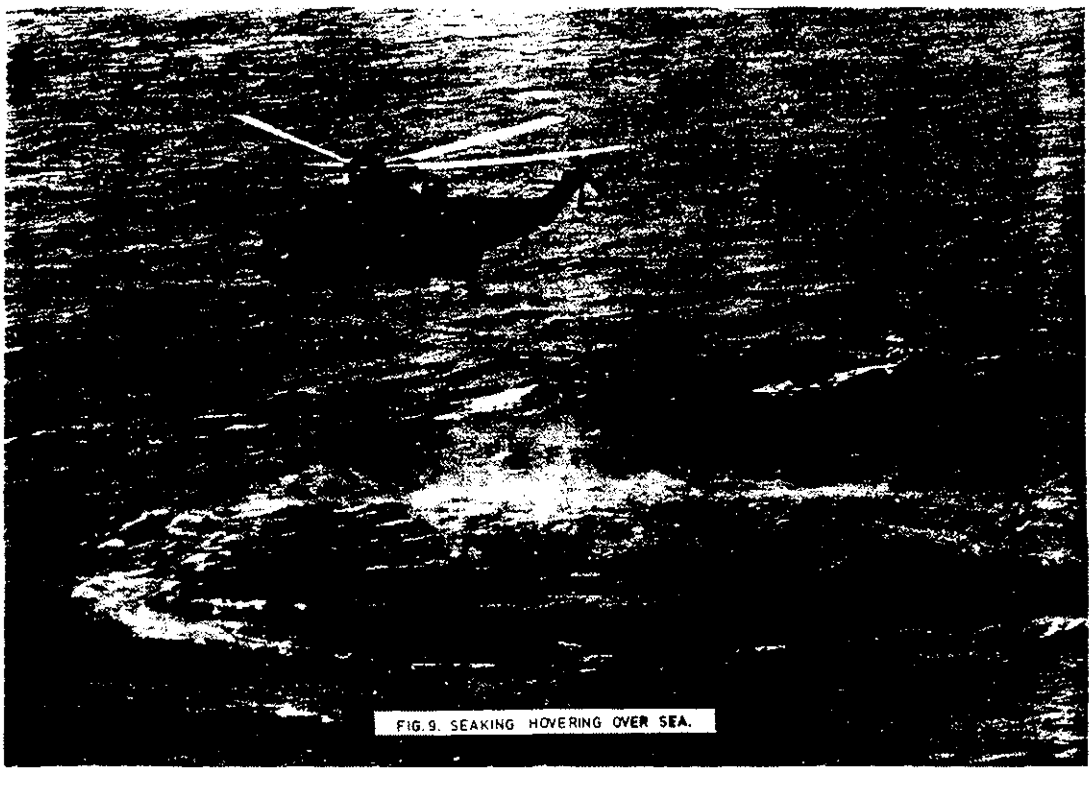


FIG. 9. SEAKING HOVERING OVER SEA.

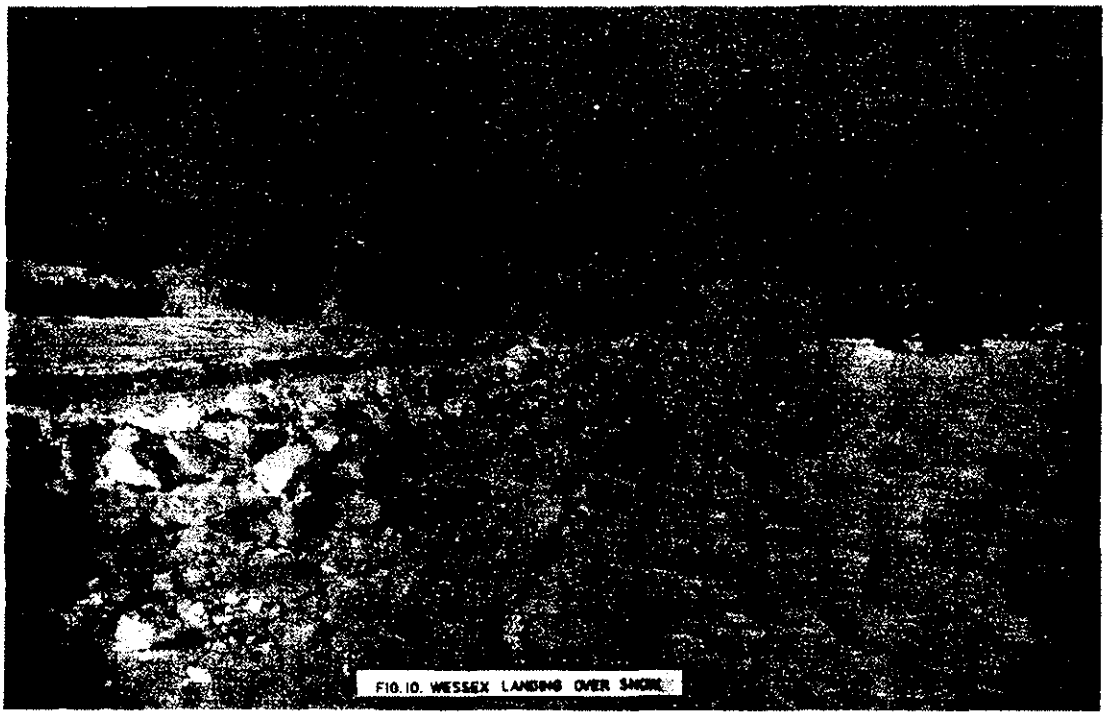
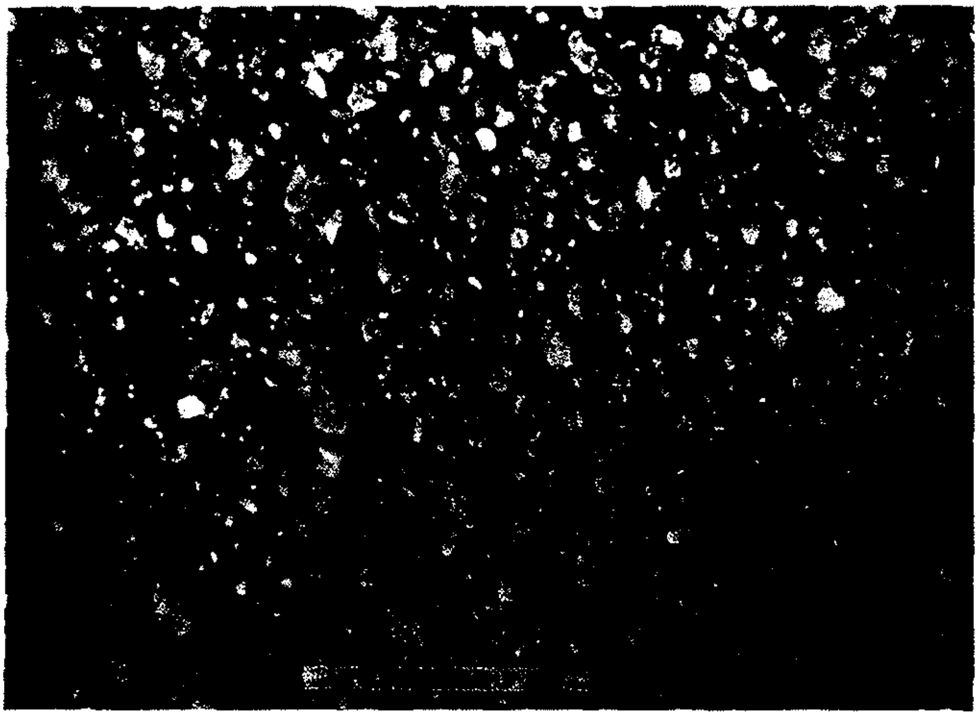


FIG.10. WESSEX LANDING OVER SNOW



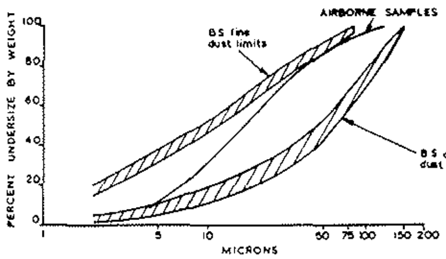


FIG. 13 SIZE ANALYSIS LIMITS OF BS 1701 TEST DUSTS AND TYPICAL WEIGHT DISTRIBUTION OF AIRBORNE SAMPLES COLLECTED UP TO 40 FEET (WESSEX SAND TRIALS)

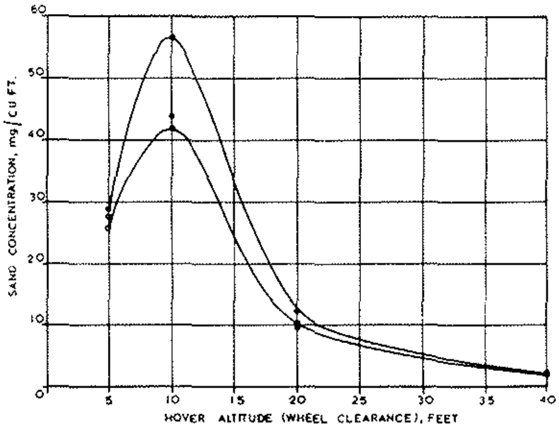
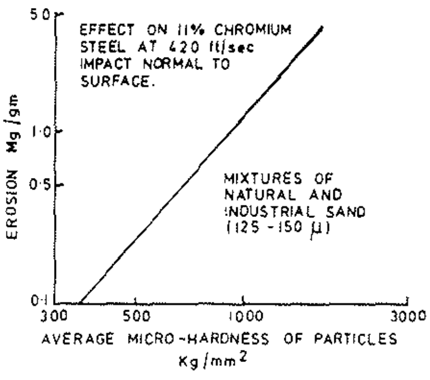
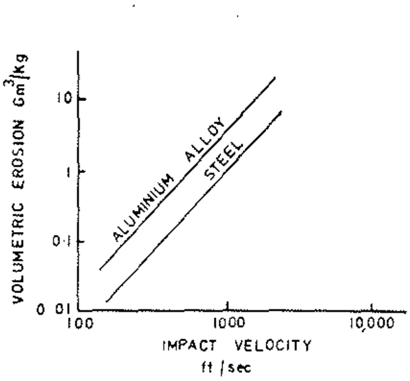


FIG 14 AIRBORNE SAND CONCENTRATION AGAINST ALTITUDE

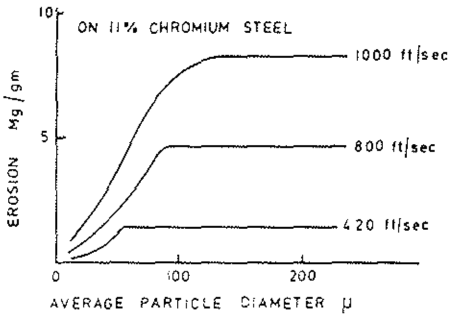
SHOWING TOP AND BOTTOM LIMITS OF SCATTER EXPERIENCED DURING WESSEX SAND TRIALS (MEASURED AT ENGINE INTAKE)



EFFECT OF HARDNESS



EFFECT OF VELOCITY



EFFECT OF PARTICLE SIZE

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

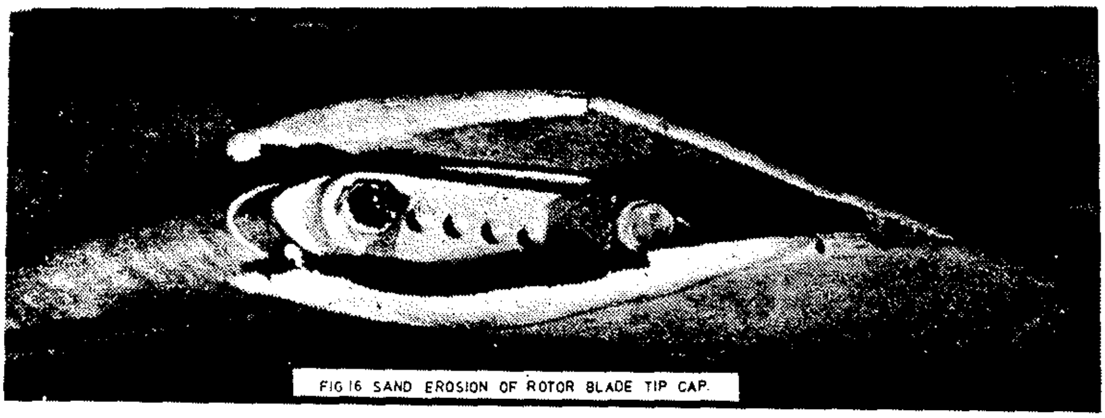


FIG 16 SAND EROSION OF ROTOR BLADE TIP CAP.

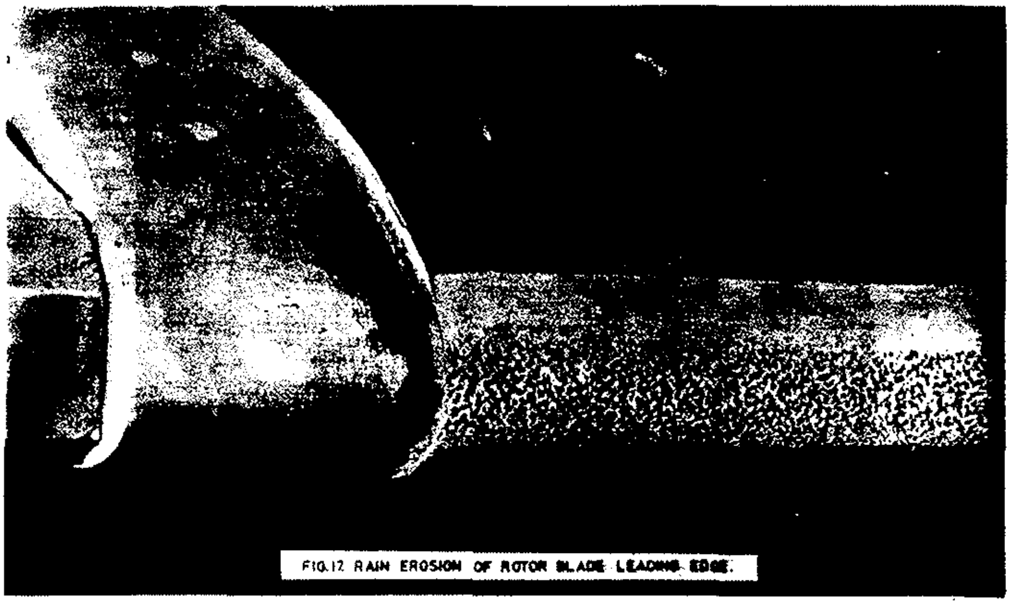


FIG.17 RAIN EROSION OF ROTOR BLADE LEADING EDGE.

FIG.18a. WESSEX TAKING OFF OVER STRAW STUBBLE.

FIG 18b LOOSE VEGETATION OVER SCOUT INTAKE.

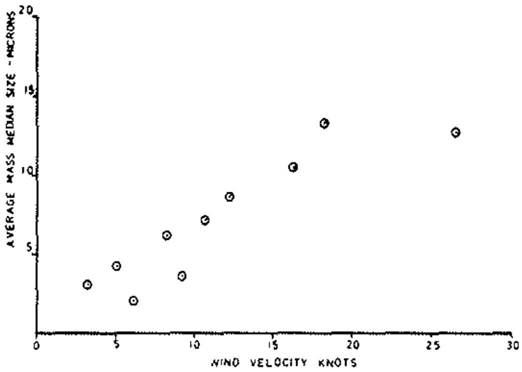


FIG. 19 AVERAGE MASS MEDIAN SIZE OF SEA-SALT AEROSOL, AGAINST WIND VELOCITY WHICH PRODUCED IT (N.A.E.C. DATA FROM SEA LEVEL TESTS AT KEY WEST)

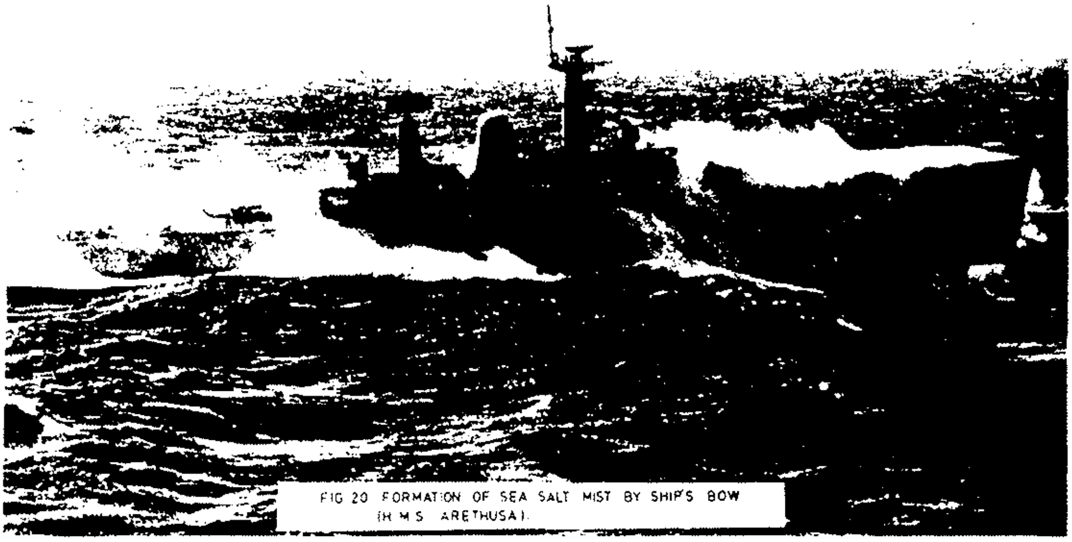


FIG 20 FORMATION OF SEA SALT MIST BY SHIP'S BOW (H.M.S. ARETHUSA).

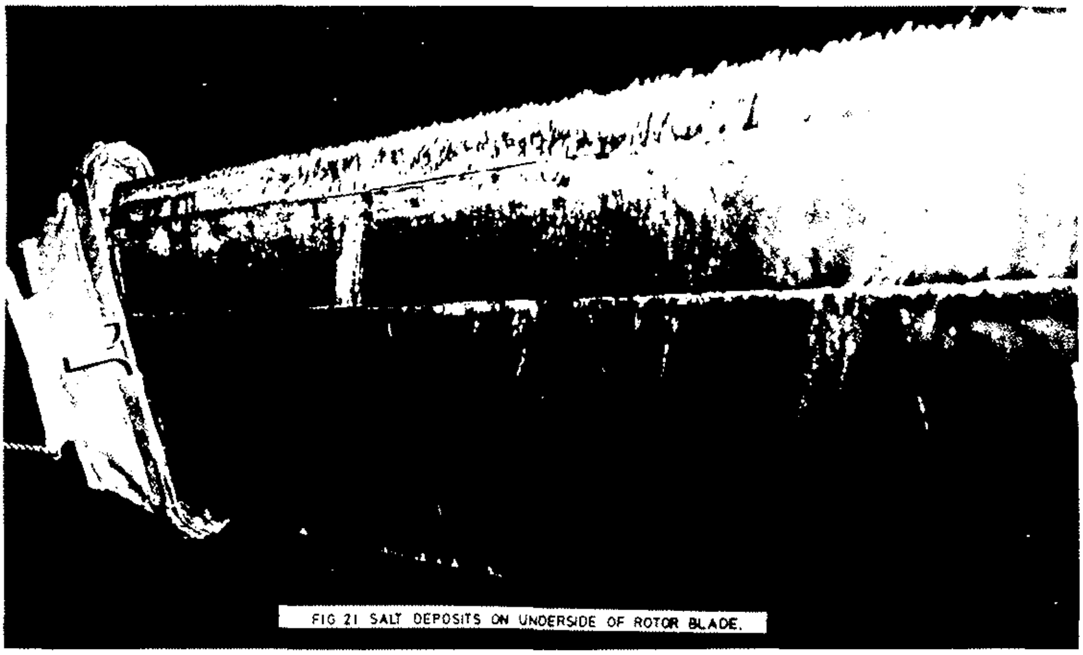


FIG 21 SALT DEPOSITS ON UNDERSIDE OF ROTOR BLADE.

FIG 22 FORMATION OF SEA SALT MIST BY HIGH WIND.

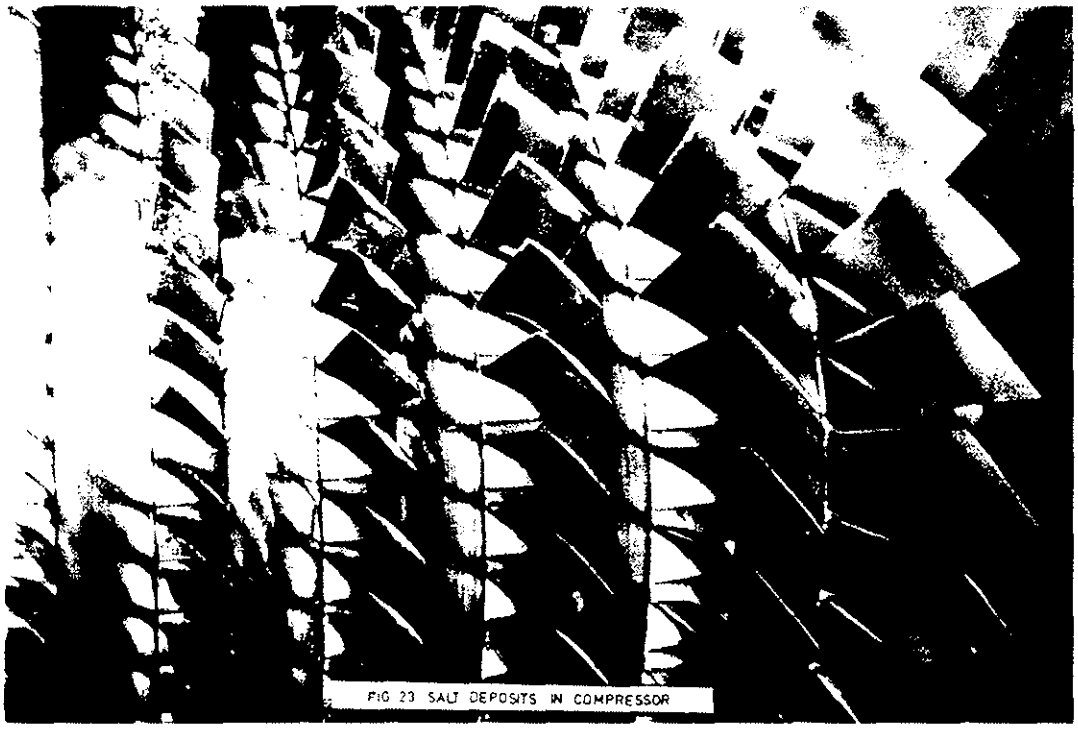


FIG 23 SALT DEPOSITS IN COMPRESSOR

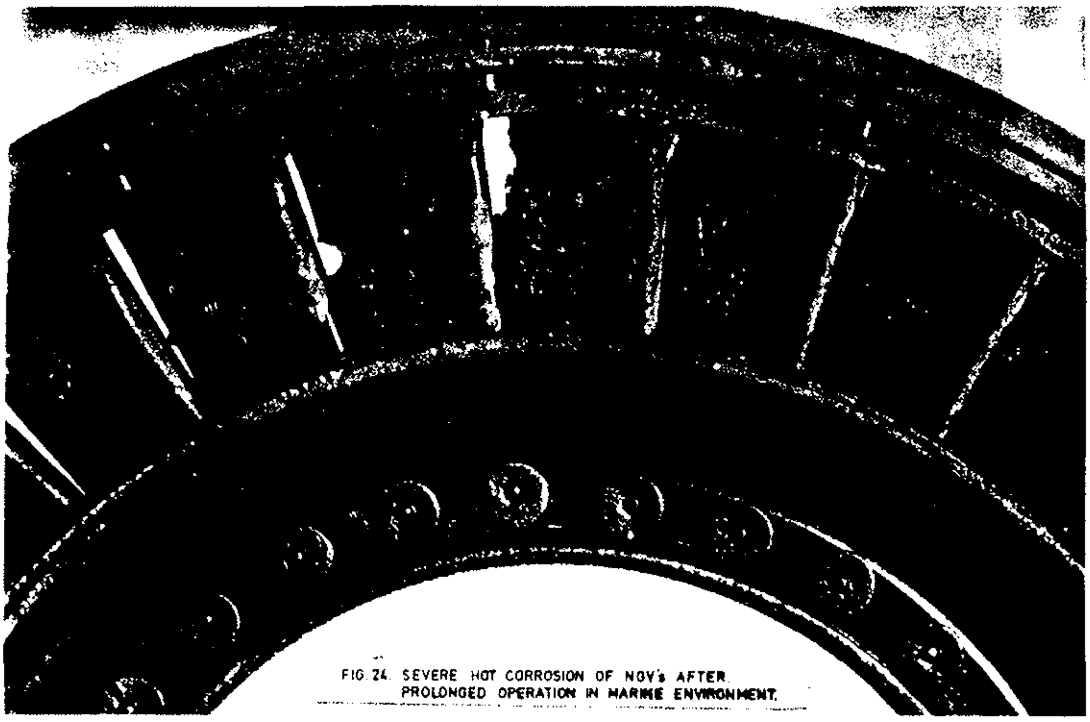


FIG. 24. SEVERE HOT CORROSION OF NGV's AFTER PROLONGED OPERATION IN MARINE ENVIRONMENT.

FIG. 25. SEM PICTURE OF SALT PARTICLE EMBEDDED IN TURBINE BLADE (X 1400).

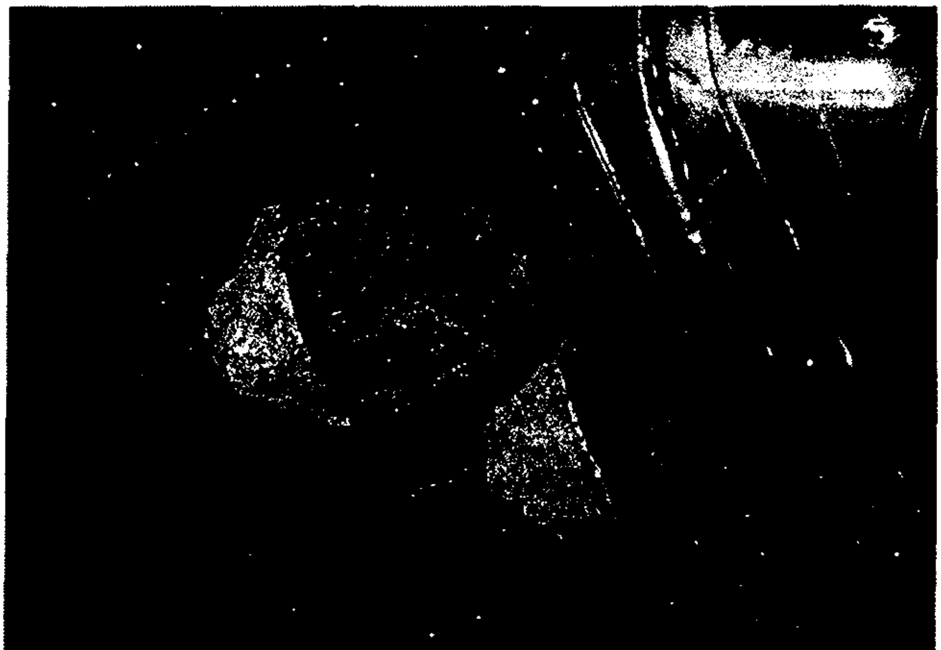


FIG 26. CLEAR ICE ON AIRFRAME FITTING AFTER 31 MINS IN STRATUS CLOUD AT −1·5°C AND 130 KTS.

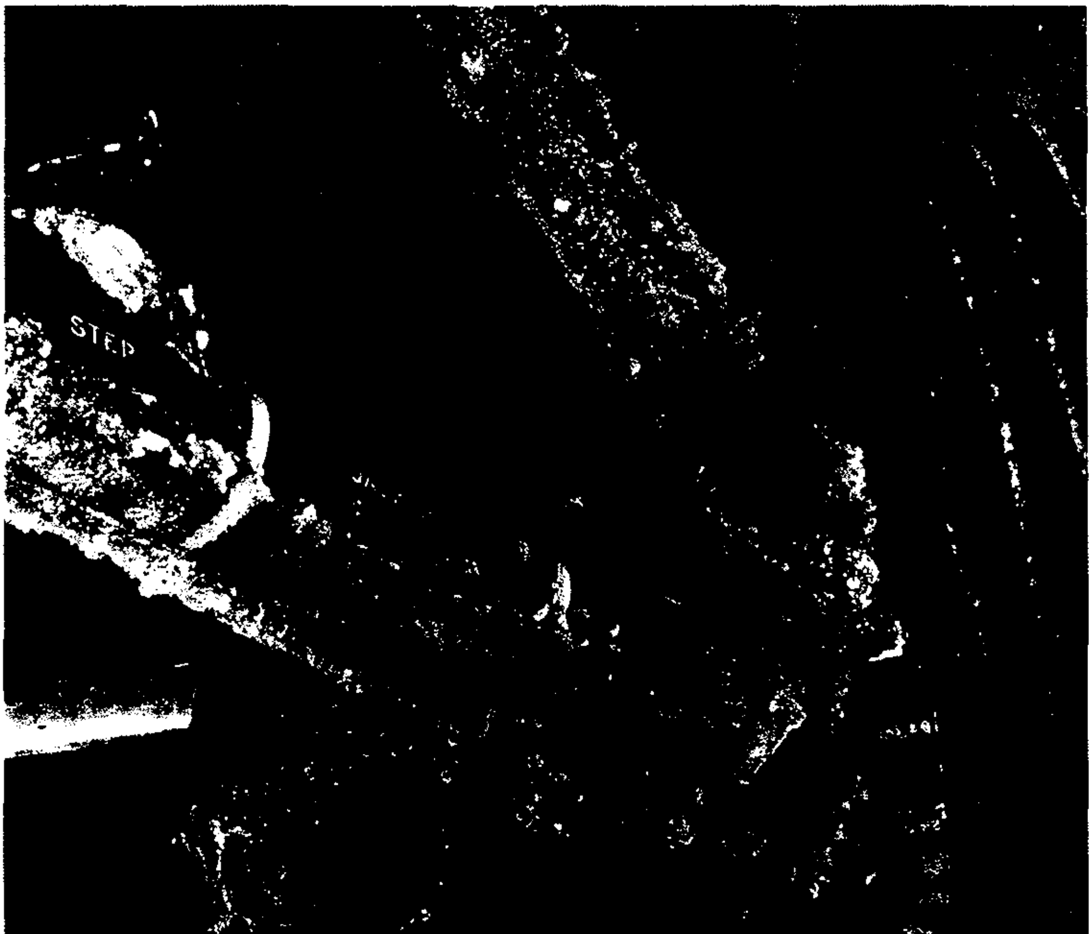


FIG. 27 CLEAR ICE ON UNDERCARRIAGE AFTER 60 MINS IN ICING CLOUD AT ~ 0 TO −1°C.

FIG. 28. 64 MINS IN ICING CLOUD AT 1·4°C.

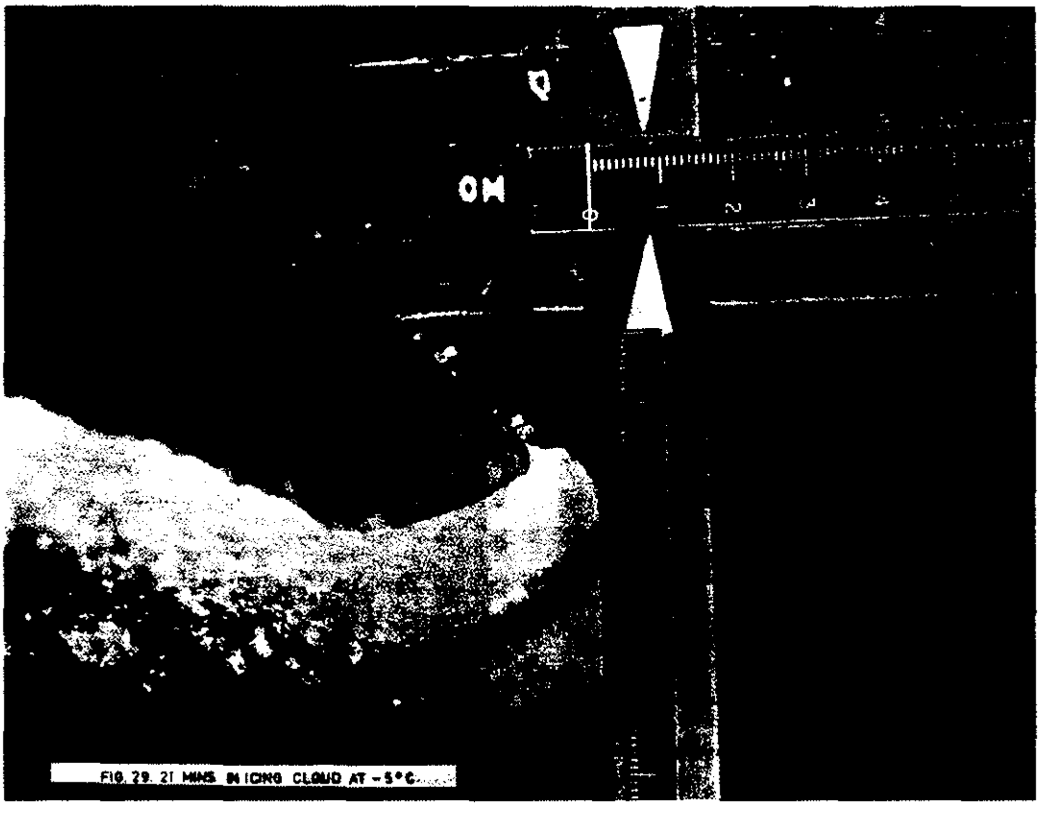


FIG. 29. 21 MINS IN ICING CLOUD AT −5°C.

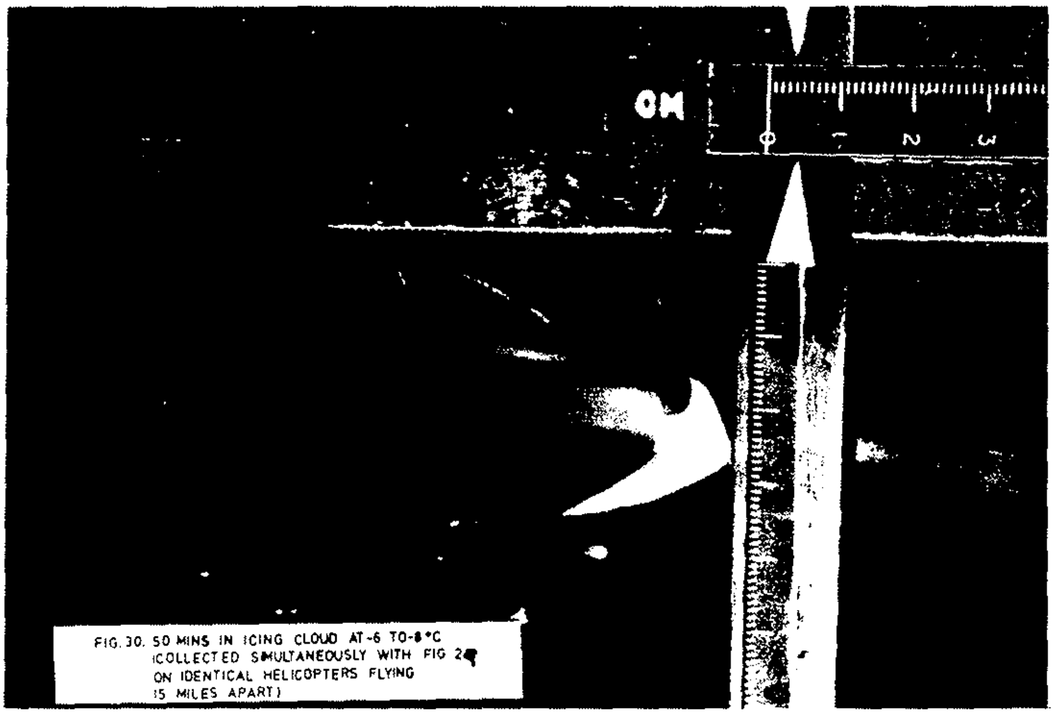


FIG. 30. 50 MINS IN ICING CLOUD AT -6 TO -8°C
(COLLECTED SIMULTANEOUSLY WITH FIG 29
ON IDENTICAL HELICOPTERS FLYING
15 MILES APART)

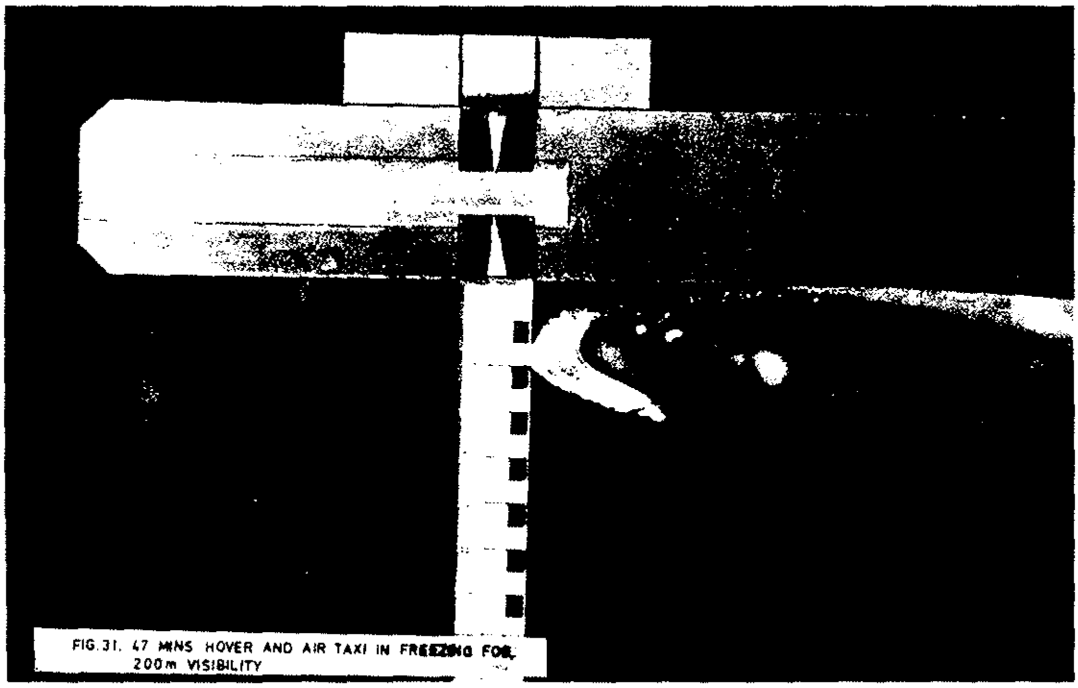


FIG. 31. 47 MINS HOVER AND AIR TAXI IN FREEZING FOG,
200m VISIBILITY

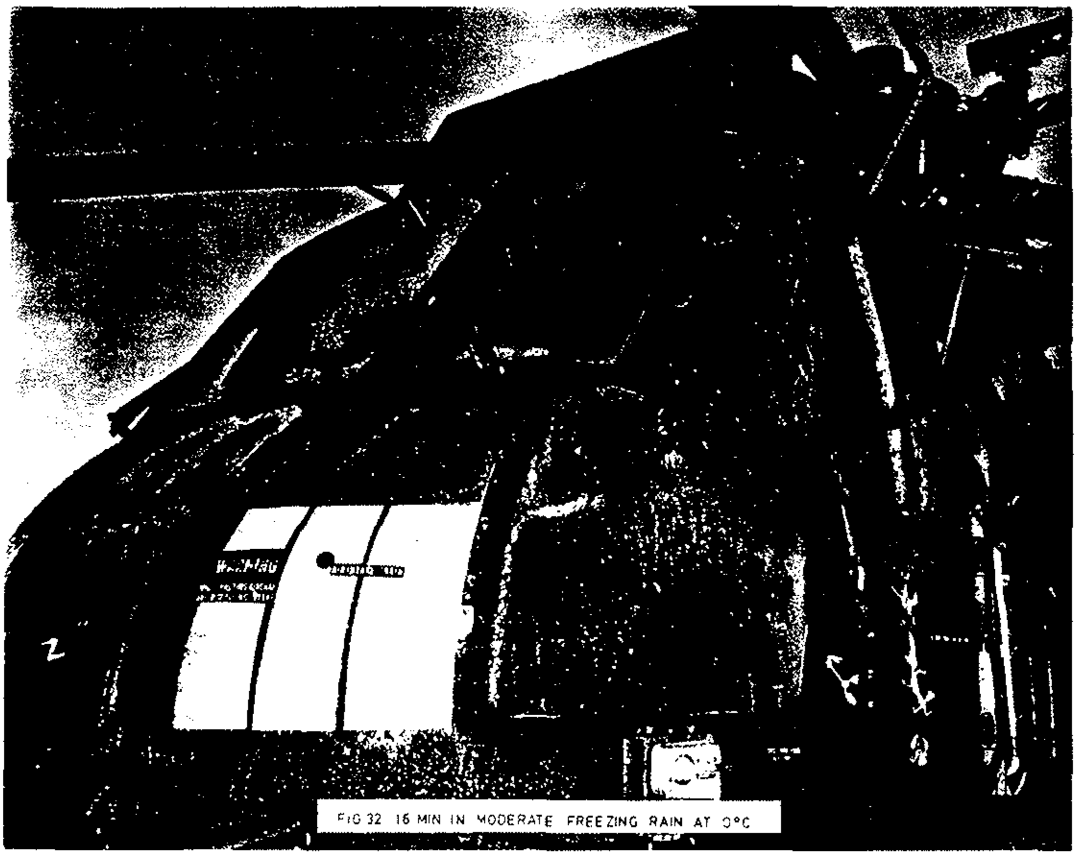


FIG 32 16 MIN IN MODERATE FREEZING RAIN AT 0°C

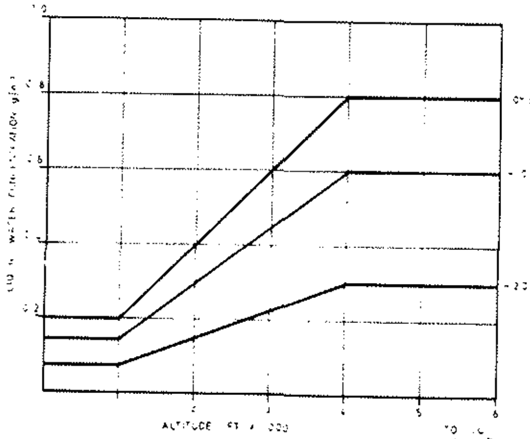


FIG 33 CONTINUOUS MAXIMUM CONDITIONS FOR HELICOPTERS PROPOSED BY McNAUGHTAN (25) 0 TO 10,000 FT, 20 μ VOLUME MEDIAN DIAMETER. WITHIN THIS ENVELOPE ASSUME A PROBABILITY OF INTERMITTENT ENCOUNTERS EVERY 50 MILES, 4 MILES EXTENT, OF TWICE CONTINUOUS VALUE

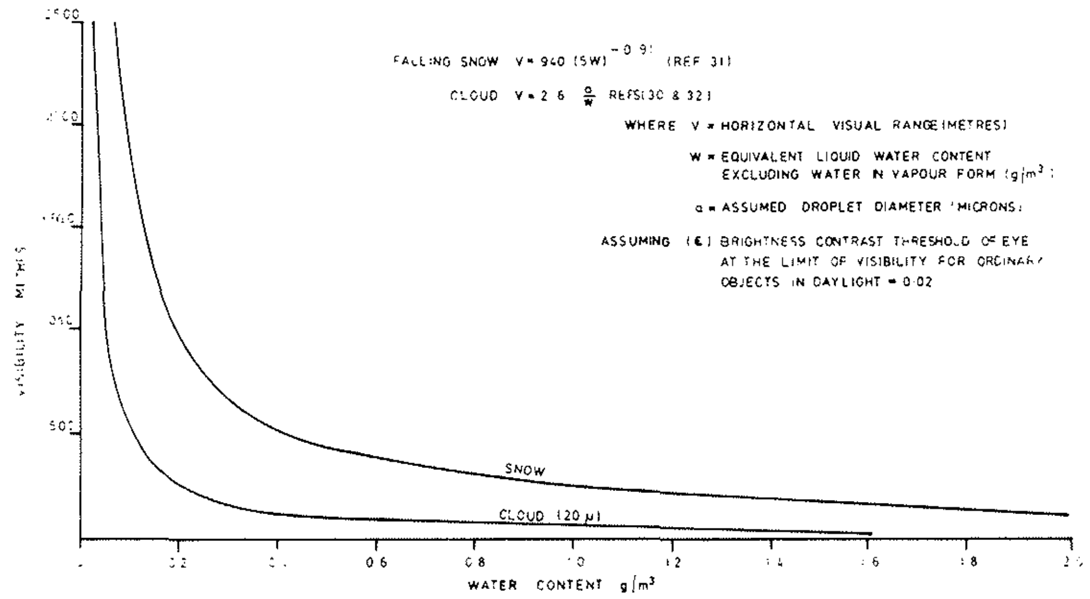


FIG. 34. EXAMPLES OF CALCULATED HORIZONTAL VISUAL RANGES IN SNOW AND CLOUD.