SCHEMES FOR DE-ICING HELICOPTER ROTOR BLADES

HYBRID HEATER/PASTE AND HEATER/ FLEXIBLE COATING

BY

J. H. SEWELL, L.R.I.C.
(Materials Department, Royal Aircraft Establishment)
AND G. OSBORN, GRAD. R.I.C.
(formerly Naval Aircraft Materials Laboratory)

This article was presented by the authors as a paper at the Fourth European Rotorcraft and Powered Lift Aircraft Forum held at Stresa, Italy in September 1978 and was published in the October 1979 issue of the Journal of Naval Science

Introduction

During helicopter flight in icing conditions, ice tends to accrete on the unprotected main rotor blades and will increase in thickness until it is shed. Even relatively small accretions can cause the blade torque required to maintain level flight to rise above permitted limits. Furthermore, heavier accretions or uneven shedding can result in unacceptably high vibration levels; helicopter rotor blade protection is therefore considered very necessary.

As a concept, heated rotor blades would appear to offer a possible long-term technical solution to the problem of rotor icing. However, at the time of writing, an electrothermal scheme which will operate efficiently in all icing conditions has yet to be demonstrated. There are also high cost, power, weight, and maintenance penalties involved in heating rotor blades. Most helicopters in service with the U.K. Armed Forces would be exposed to the risk of flying in icing conditions during only a few months of every year but would be carrying unnecessary extra weight with attendant increased fuel and maintenance costs (and of course a lower payload) for the remainder of the period and therefore for the greater part of their service lives. The task of retro-fitting existing helicopters with heated blades would naturally be a costly modification with resultant deleterious effects on aircrafts' performances for reasons already described.

One of the alternatives to electrothermal de-icing is chemically formulated pastes which either prevent ice formation or improve shedding. Although pastes would invariably have to be replenished before each flight, performance penalties would only exist whilst the paste was actually on the blade; also the additional cost, power, and weight penalties would be low, and maintenance, apart from application and removal, would be minimal. However, as a result of small-scale wind tunnel tests and subsequent flight trials, chemical pastes have been shown to be susceptible to both rain and ice particle erosion in the stagnation region of the blade.

Composite flexible coatings represent another possible system for the protection of rotor blades. These comprise an outer surface bonded to a flexible sponge rubber substrate which is in turn bonded to the blade. Laboratory tests have shown that such a system affords a very low adhesion to ice, but subsequent wind tunnel tests and flight trials revealed that accreted ice could remain on the stagnation region of the blade to the detriment of the aerodynamic properties. This article describes hybrid systems in which a narrow chord heater mat is used for anti/de-icing the stagnation region of the blade and aft of this, on both the upper and lower surfaces of the blade, is applied either a paste or a flexible substrate coating. In investigating these schemes, it was hoped to utilize the good aspects of both and to eliminate their deficiencies as far as possible. For example, the heater would deal with ice formed in the stagnation region, where the flexible substrate coating is inefficient and the paste prone to erosion, whilst the paste or flexible substrate would shed runback and accreted ice aft of the heater mat. Either hybrid combination would be lighter, less costly to operate and install, use considerably less power and be less complex than an all-heated blade protection scheme.

The Hybrid Heater/Paste System[1]

The Pastes

The pastes used in tests thus far consist essentially of gelled freezing-point depressants (e.g. ethanediol or glycerol) dissolved in a suitable solvent.[2] They also contain various other additives which impart improved resistance to shear and better adhesion. Ideally, an ice-shedding paste should be:

(*a*) easy to apply to blade surfaces at temperatures ranging from + 20°C to − 15°C;
(*b*) non-corrosive, non-toxic and present no adverse effect to blade materials;
(*c*) able to remain on the blade and be effective for at least the duration of one flight;
(*d*) able to preserve, as far as possible, the aerodynamic properties of the blade;
(*e*) capable of shedding ice continuously such that no observable in-flight torque rises occur when flying in standard icing conditions;
(*f*) easily removable from the blade surface;
(*g*) made of inexpensive and readily available materials;
(*h*) capable of being stored for an adequate length of time.

In addition, as high a proportion of the total volume of paste as possible should be available for depressing the freezing point of water and thus preventing the formation of ice. However, some ice build-up on a paste could be acceptable provided that the ice melts at the paste/ice interface and is thus shed readily as a result of aerodynamic and centrifugal forces prevailing on a rotating blade.

Paste Application

Since the pastes are in the form of a stiff gel at room temperature, a source of heat to facilitate melting them is necessary in any service or indeed laboratory environment. Suitable means of heating have been receptacles containing hot water or the more complex but rapid hot spray cup (described below). The original pastes were made exclusively for brush application, but later developments included formulations for spraying. In the case of spray application, the DeVilbiss Company, Poole, Dorset was consulted[3] and the following equipment (see FIG. 1) and conditions were found to be successful:

Spray gun	—	DeVilbiss Model JGA–541
Air Cap	—	Type 306
Fluid Needle	—	Type D–EX
Air Pressure	—	250–350 kN/m^2
Air Flow	—	approx 270–350 dm^3/min
Spray Cup	—	DeVilbiss Model 7600–500 complete with electrical power cable for 240V, 50Hz supply.

FIG. 1—DEVILBISS MODEL JGA-541 SPRAY GUN COMPLETE WITH HOT SPRAY CUP. THE CUP IS HEATED USING A NORMAL 240V MAINS POWER SUPPLY WHICH IS DISCONNECTED IMMEDIATELY PRIOR TO SPRAYING

The fluid needle adjustment was set arbitrarily to give the optimum spraying results for each individual paste, and the spreader adjustment valve was set to give the minimum fan angle.

Spraying tests were carried out in an 'arctic chamber' at ASWE, Portsdown, in order to simulate application under sub-zero conditions. The compressed air delivery temperature to the gun will be at or near the outside air temperature, consequently this will cool the molten paste immediately prior to atomization giving an uneven delivery from the gun and adverse film formation. These effects would be alleviated to some extent by insulating certain parts of the gun, thus preserving the temperature of the liquefied paste. Pastes formulated for spray application were tested in the range + 5°C to − 15°C.

The Heater

Originally, wire heaters of width 25 mm were constructed in the laboratory for successful feasibility studies, but it was realized that these would be unsuitable for flight conditions. As a result, metal-foil element electrical heater mats were prepared and bonded by Dunlop Ltd., Aviation Division, Coventry to the leading edges of two 750 mm long Wessex helicopter main rotor blade sections. The heater mats were of a complex sandwich construction employing polyurethane rubber as the exposed surface material. In all, two heater mats were constructed, one being 40 mm wide the other 50 mm; each was 480 mm long and, when in their bonded positions, extended chordwise further on the underside than on the upper side. Thermocouples were positioned in the mat (see FIG. 2) such that the element temperature could be monitored continuously.

Method of Testing

The blade sections were installed at + 8° incidence in the working section of an icing wind tunnel operated by Lucas Aerospace Ltd., Artington, Surrey. The tunnel section was rectangular, being 300 mm high and 500 mm wide. The wind speed was maintained at 100 m/s. The static temperature could be varied between ambient and − 20°C. Water droplet sizes were between 20 and 40 μm and the liquid water concentration in the air stream was adjusted so that 'continuous maximum' icing conditions were achieved.

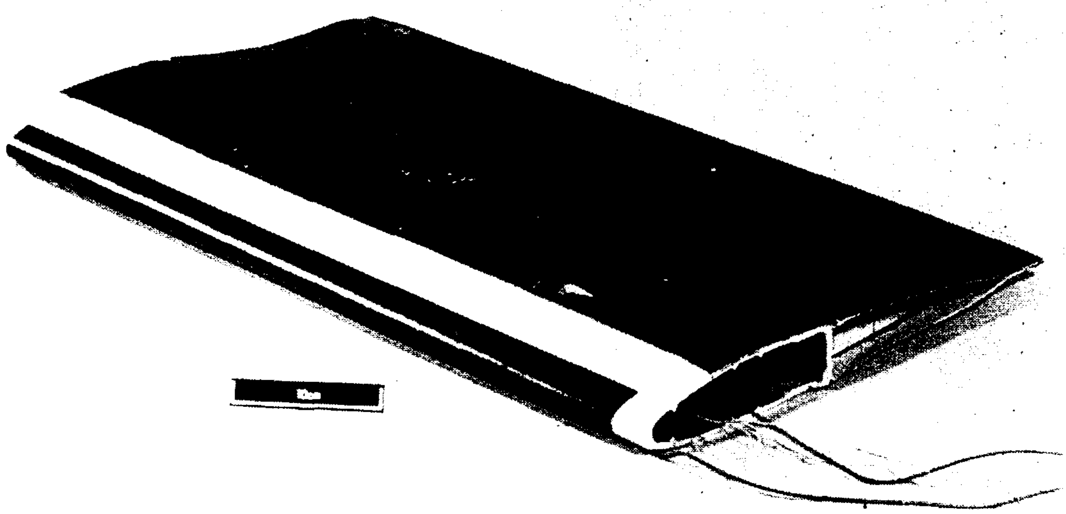

FIG. 2—WESSEX MAIN ROTOR BLADE SECTION COMPLETE WITH BONDED 50 MM WIDE HEATER MAT

Test Results and Discussion of Hybrid Heater/Paste Scheme

So far two groups of tests have been carried out: the first utilized the 40 mm and 50 mm heater mats and a number of different pastes, the second group employed exclusively the 50 mm strip in conjunction with only one paste.

Performance of Pastes

Despite the advantages offered by the hybrid paste/heater system, it is nevertheless desirable to have a fairly resistant and adherent paste even though it no longer covers the stagnation region. Therefore, pastes showing both good adhesion and good ice-shedding properties were further tested for ice-particle erosion resistance. Although several pastes performed satisfactorily, one in particular offered a good all-round performance and was, exceptionally, both sprayable and brushable. This paste had, incidentally, been flight tested in Canada in early 1977 and was therefore selected to be the participant in the second group of tests.

Other points to be noted concerning the performance of the pastes were as follows:

(*a*) The design of the heater mats does not include a gradual blend into the blade section aerofoil, such that a definite 'step' exists aft of the mats which appeared to afford some degree of protection to the pastes. When pastes were applied in thicknesses greater than the height of this step, they would tend to lift and tear even in clear air conditions. This being the case, it is hoped that such a step can be incorporated in any future design provided that there are no aerodynamic penalties.

(*b*) The spray method of application is more efficient than brushing and gives a smoother and more uniform coating even onto a substrate cooled to − 20°C.

The logistic disadvantages of having a spray system requiring both compressed air and electrical supplies in remote airfield hangars and under shipboard conditions may be outweighed when one considers the severe time penalty attendant with brush application. It is estimated that one hot spray cup containing approximately 1 litre of paste would be sufficient for coating one Sea King helicopter main rotor blade.

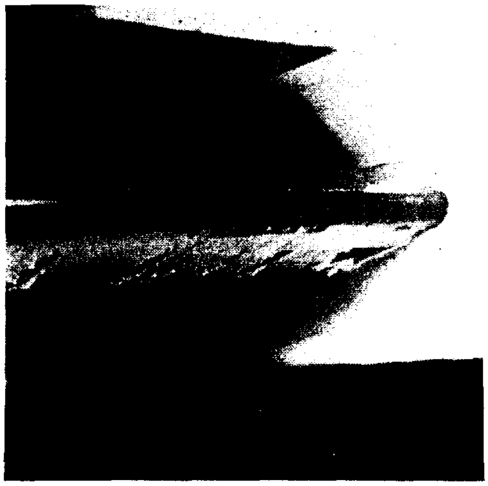

FIG. 3—WESSEX MAIN ROTOR BLADE SECTION WITH HEATER MAT AND PASTE UNDERGOING ICING TESTS IN THE ARTINGTON WIND TUNNEL

Performance of Heater Mats

The performance of the heater mats was assessed with regard to the power required just to anti-ice at a given tunnel temperature and the element temperature at that power input and, under de-icing conditions, the average thickness of accreted ice before shedding, again at a given tunnel temperature and power input/element temperature. In cases where the mats were operated in icing conditions without the pastes, there was build-up of run-back ice which did not shed. When the pastes were included the ice shed continuously, the initial degree of accretion depending upon the individual efficiency of the pastes. See FIG. 3.

The 50 mm mat was found to be more efficient than the 40 mm in terms of power required for a given performance. At present, the reasons for this are not fully understood.

Results of the second group of tests show that the 50 mm mat is capable of anti-icing down to − 19°C. At −20°C there was slight ice accretion but shedding always occurred before the ice had reached 7 mm in thickness. The de-icing and anti-icing thresholds shown in FIG. 4 represent continuous power application to the whole of the heater element and no attempt was made to cycle the power supply.

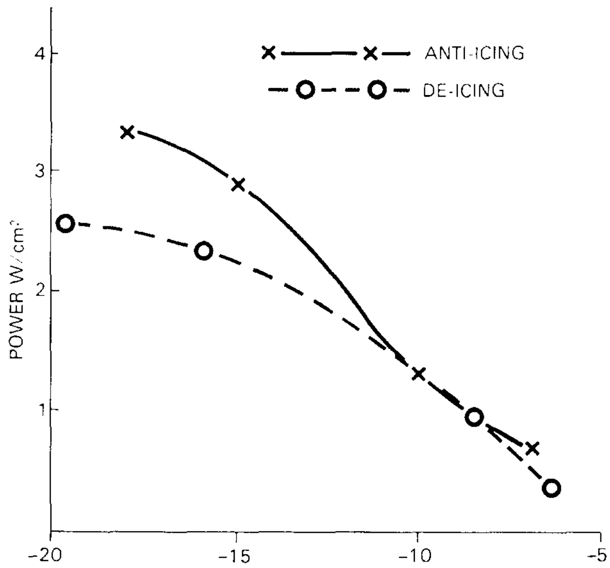

FIG. 4—ANTI-ICING AND DE-ICING THRESHOLD, 50 MM MAT

Hybrid HRB/Flexible Coating

Some factors governing ice shedding

Consider a drop of water at rest on a solid, non-deformable surface and making a contact angle with the surface between 0 and 180°. Attractive van der Waals' dispersion forces will operate between the water molecules and the surface, together with additional forces if the latter is polar. These forces will persist after the water drop freezes, even though stresses induced during solidification and expansion of the water on freezing may tend to weaken the bond so that ice will adhere to some extent even if the surface in non-polar and relatively hydrophobic. A low-energy surface presents a greater contact angle to water than does a high-energy surface and tends to assist the formation of air bubbles at the ice/surface interface; both of these phenomena should help to weaken the adhesion. The lowest critical surface tension of a polymer in common use is about 18·5 mN/m for polytetrafluoroethylene (PTFE), although lower values have been reported for some experimental polymers. As expected, ice adheres well to PTFE when the polymer is in the form of a block thick enough for the surface to be inflexible, so a low surface energy alone is not necessarily the only parameter to be considered when devising a surface having low adhesion to ice.

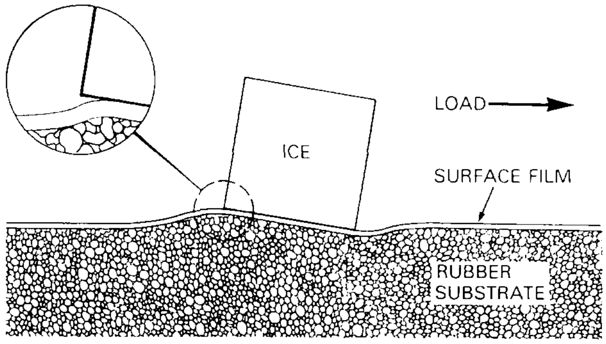

FIG. 5—ICE PEELING FROM FLEXIBLE SURFACE

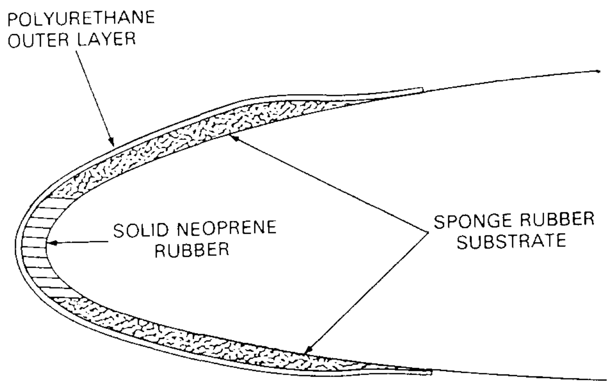

FIG. 6—SECTION THROUGH ICE-SHEDDING COATING ON LEADING EDGE OF HELICOPTER ROTOR BLADE

An attempt is usually made to remove one material from another by peeling. The adhesives technologist tries to avoid peel situations when designing for maximum strength because the applied stress is concentrated on only a very limited area of the interface at any one time during peeling; the high local stress concentrations produced therefore greatly reduce the load required to part an adhesive from an adherent compared with that required to part the same materials when under simple tension. The tensile and resultant shear stresses necessary to remove ice from a suitably flexible surface should therefore be less than those required to remove ice from a non-deformable material having otherwise identical surface properties. The removal of ice from a flexible surface should be facilitated by the absence of plastic deformation under stress at the crack tip in the surface of the material to which the ice is bonded. A low energy surface which is sufficiently flexible to allow peeling but which resists plastic deformation over a small area such as that involved in the vicinity of a crack tip appears to be the compromise required to promote ice-shedding under load. See FIG. 5.

Flight trials of flexible coatings

Deformable surfaces can be made by bonding to an existing structure a composite comprising a sponge rubber substrate carrying an outer surface of a flexible foil or film. A coating consisting of 0·64 mm thick polyurethane rain-erosion resistant sheet on 1·6 mm thick closed-cell natural rubber sponge was originally proposed for flight trials as a result of laboratory experiments which indicated that the coating afforded relatively low adhesion to ice. However, tests revealed that the soft substrate would be destroyed by droplet impact through rain, so the sponge rubber around the blade leading edge in the area prone to erosion was replaced by a hard solid rubber strip. This modified coating was applied to two opposite rotor blades of a Wessex 5 helicopter, the other two blades being uncoated so that ice-shedding comparisons could be made. See FIG. 6.

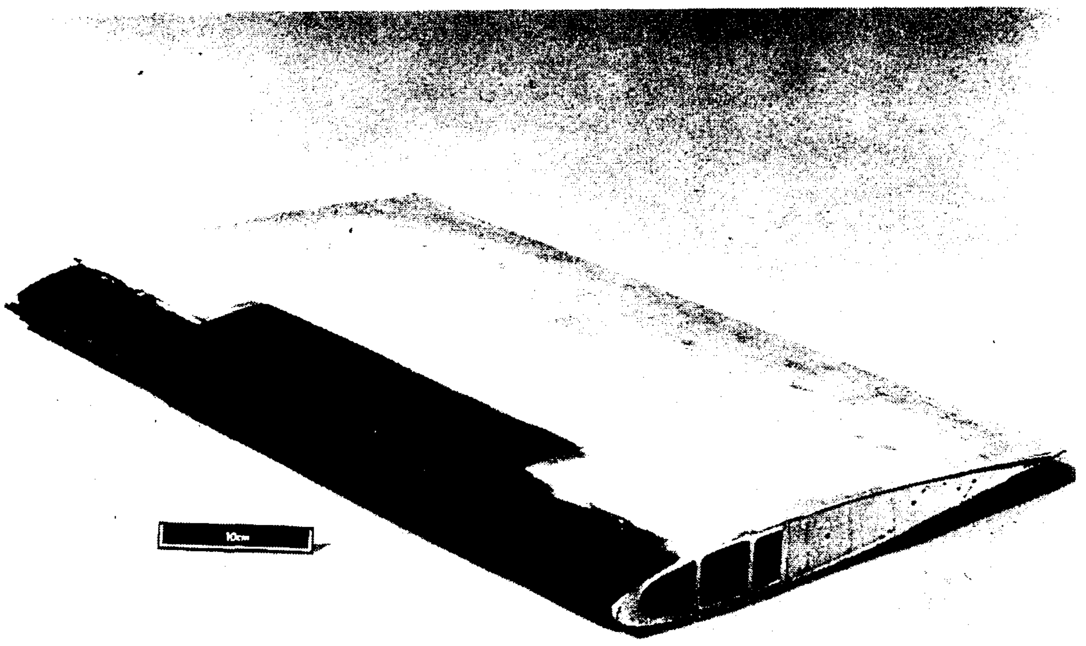

FIG. 7—WHIRLWIND MAIN ROTOR BLADE SECTION WITH HEATER MAT AND FLEXIBLE COATING

Flight trials were made at Tirstrup, Denmark, but in the climatic conditions encountered (the air temperature did not fall below – 5°C), ice formed only on the stagnation region of the blades and not on the parts of the coating where the flexible sponge rubber substrate was present. Thus as ice formed on hard, inflexible surfaces on both modified and unmodified blades, no difference in shedding characteristics would have been expected, or was, in fact, observed. It was considered impracticable to develop a flexible erosion-resistant leading-edge coating since distortions would inevitably occur in this aerodynamically sensitive region which could seriously degrade the performance of the blade. A hybrid de-icing system comprising a flexible substrate composite coating on both upper and lower blade surfaces aft of an electrically-heated leading edge was therefore proposed. The aim was to shed or to prevent ice forming on the heated zone and to allow run-back and accreted ice to be shed under centrifugal and aerodynamic forces from the flexible coating. See FIG. 7.

Development of hybrid scheme: Laboratory tests on flexible coatings

An investigation was made to find the best materials for the composite flexible substrate coatings. It was decided to retain the 1·6 mm thick closed-cell natural rubber sponge as the substrate and to concentrate on the properties of the outer surface. Surface materials chosen for initial evaluation were shim steel, copper, copper-beryllium, phosphor bronze, low density polyethylene, and nylon 6. Films of these materials, measuring about 80 × 100 mm, were bonded to the sponge rubber substrate of the same dimensions which was in turn stuck down to a rigid metal backing plate, a flexible adhesive being used throughout.

The shear adhesion of ice to the various composite test surfaces was measured as this form of loading most closely resembled the forces on ice accreted on rotating blades. Inside a freezer cabinet, a circular wooden block 5 mm thick with a strip of woven cotton bonded to the upper face was placed on the experimental surface and the gap between the lower face of the block and the surface filled with distilled water. This was allowed to freeze at – 16°C for 20 min with a load of 100 g on top of the block; the frozen area was 5 cm^2. Ice adhesion was determined by attaching a scale pan to the end of the cotton strip, securing the base of the experimental surface on a horizontal platform in the freezer cabinet, passing the cotton strip over a pulley so that the pan hung vertically and loading the latter with 250g weights every 15 seconds until failure occurred. At least ten measurements were made on different parts of each surface and a statistical analysis of variance was used to see whether the ice adhesion values for the various surfaces were significantly different. In order to investigate the relationship between ice adhesion and surface flexibility under load, the 5 mm diameter flat base of a dial gauge was positioned vertically touching the experimental surface. Loads were applied to a pan on top of the dial gauge rod and the indentation against load recorded. The relative water wettabilities of the metal samples were compared with the ice adhesion results to see whether any correlation existed. Distilled water (0·5 cm^3) was deposited on to the vapour-degreased metal surface bonded directly to a rigid substrate and the area covered by the water was measured—the larger the area the more wettable the surface.

TABLE I—*Shear adhesion of ice to metal and polymer films having 1·6 mm thick flexible sponge rubber substrates*

Sample No.	*Film or foil*		*Shear adhesion of ice (kN/m^2)*	
	Type	*Thickness (mm)*	*Mean*	*Standard deviation*
1	Shim steel	0·076	43·9	25·1
2	Shim steel	0·127	48·0	21·7
3	Commercial copper	0·076	39·3	11·4
4	Hard copper	0·102	52·6	22·3
5	Copper beryllium, half hard	0·076	53·7	19·8
6	Copper beryllium, half hard	0·102	60·4	27·9
7	Phosphor bronze	0·152	68·0	37·1
8	Polyethylene, low density	0·127	36·4	12·0
9	Polyethylene, low density	0·254	25·8	6·7
10	Polyethylene, low density	0·508	46·4	24·0
11	Nylon 6	0·254	62·2	28·6
12	Shim steel, 50 mm wide strip	0·076	44·1	17·0
13	Copper beryllium	0·076	48·0	14·9
14	Commercial copper on 3·2 mm thick sponge rubber substrate	0·076	42·9	6·6

Test results and discussion of Hybrid Heater/Flexible Coating Scheme

The shear adhesion of ice to the composite coatings is given in TABLE I. Tests using square wooden blocks instead of circular ones of the same area showed no significant difference on ice adhesion. Increase in surface flexibility resulted in lower ice adhesion values for the polyethylene samples tested but no correlation was found between flexibility, water wettability and ice adhesion for the metals although the adhesion of ice to these samples was considerably lower than would be expected if the sample surfaces were rigid. Despite a large standard deviation from the mean in several cases, the analysis of variance showed that ice adhesion to the various surfaces was significant to greater than 0·1 per cent.; this indicated that it was possible to place the different test samples in order of relative ice-shedding ability.

A relationship between the ice-shedding behaviour of a coating in the laboratory and on a rotating helicopter blade in flight is difficult to predict because in the latter case a much larger area of ice is usually shed at any one instance than the 5 cm^2 area that was removed in the laboratory tests. Ice adhesion per unit area tends to decrease with increase in area of adhesion and also aerodynamic forces which assist ice release are difficult to simulate in laboratory tests. However, a load parallel to the test surface which was applied to the cotton strip attached to the wood block during the laboratory test approximates to a centrifugal force acting through the centre of gravity of an ice block of double the wood block thickness. Calculations show that ice 25 mm thick should shed from sample 9 (see TABLE), from outboard of 60 per cent. of span on a 8·2 m long blade rotating with a tip speed of 207 m/s. However, a rotating rig test would be necessary to verify this. The metal foils which are thin enough to shed ice from rotor blades are probably not strong enough or sufficiently impact-resistant to merit further consideration; a wider selection of materials, particularly polymers, for both surfaces and substrates will be examined in the future.

Concluding Comments

It must be emphasized that work on these hybrid schemes is still continuing. There is much investigative work to be carried out concerning:

(*a*) laboratory studies of the mechanism of failure of ice adhesion on bonded flexible surfaces in order to predict the most promising composite structures for shedding ice under centrifugal and aerodynamic forces on rotor blades in flight;

(*b*) formulation of pastes providing better ice-particle/rain-erosion resistance, sprayability/brushability, and adhesion to the blade;

(*c*) improvements to the heater mat itself to give the most efficient heat dispersion and to minimize heat losses into the blade.

References:

1. Osborn, G. and Sewell, J. H., 'Improvements in or Relating to Helicopter Main Rotor Blades'—Patent application No. 26429/77 (1977).
2. Sewell, J. H., 'An Ice Shedding Paste for Application to Helicopter Rotor Blades'—Technical Report 77173, Royal Aircraft Establishment, Farnborough (1977).
3. Craine, K. to Osborn, G. and Sewell, J. H., Private communication (1975).