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ROTOR ICE PROTECTION SYSTEMS

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1. INTRODUCTION

Since research into helicopter rotor ice protection systems began in the early 1950s, upwards of twenty such systems have undergone varying degrees of development in artificial and natural icing conditions. Some of these systems have been produced in service quantities but they do not appear to have seen widespread use during operational flying, the general reliability and ice protection characteristics frequently leaving much to be desired.

The majority of practical systems tested to date have been electrothermal cyclic blade de-icing systems and their design has been based substantially on principles developed by the National Research Council (Ref. 1). Virtually all the early research work was carried out in artificial icing rigs, notably the N.R.C. Spray Rig at Ottawa, and the cyclic de-icing operating parameters and ice-shedding criteria were, of necessity, evolved with little or no test knowledge available for forward flight in natural icing conditions.

Within the past 5 or 6 years, there has been a significant build-up of trials experience of helicopter characteristics in natural icing conditions, this experience embracing both unprotected and protected rotor systems. This recent trials activity has highlighted a number of shortcomings and limitations intrinsic in the classic blade de-icing concepts and it is the purpose of the present paper to review the operating principles of cyclic rotor ice protection systems in the light of practical trials flying with unprotected and protected rotor systems in natural icing conditions.

2. CLASSIC BLADE DE-ICING PRINCIPLES

Before considering the characteristics of rotor blade ice accretion and rotor performance degradation which have been observed in flight, it is appropriate at this stage to re-state the principles upon which the design of cyclic blade de-icing systems, as developed to date, have been based.

Fundamentally, a cyclic blade de-icing system permits a finite build-up of ice on the rotor blade after which the ice is removed periodically. Where the ice removal is effected electro-thermally (this being the approach favoured by most of the Industry) it has been considered advantageous to use a fairly high power intensity for short duration. By this means only a small film of ice at the Ice/heater interface has to be melted, thereby breaking the adhesion of the ice, subsequent mechanical shedding of the ice from the blade being assisted by the centrifugal force field. By subdividing the aerodynamic and other areas to be protected into convenient segments, the total power required becomes substantially less than would the case if the entire surface were to be either anti-iced or de-iced as a complete area.

A typical segment pattern is shown in Figure 1. This arrangement relates to the Westland/Lucas Development electro-thermal ice protection system which has been under evaluation in a Wessex helicopter since 1972.

At an early stage in the research it was propounded that the ice removal performance of a cyclic blade de-icing system might depend critically on the energising time on each segment of the system and on the thickness and mass of ice which was permitted to form between de-icer heating. Thus, for example, an excessively long energising period, or heat ON time, might result in the production of water at the blade surface due to over-melting of the ice with a possibility of runback re-freezing on unprotected blade surface. Additionally, premature heating with insufficient ice accretion present on the blade might result in failure of the ice to shed and over-melting of the ice again with consequential runback-refreezing. These effects were studied by the NRC in the Spray Rig at Ottawa (Reference 1) and this work led to the concept of an 'Optimum Cycle' with ice-shedding criteria based on heat ON and heat OFF times which had been systematically investigated during spray rig testing to produce a clean, runback-free, ice shedding pattern.

The heat ON time was found to be a function of heater mat power intensity, the heat transfer properties and the ambient temperature. Heat ON times and heat cycle times (heat cycle time - heat ON time x number of segments), as used on the Wessex system are shown in Figure 2. This relationship is fairly typical of present day practice, relating particularly to power intensities of 20-30 Watts per sq. in. An increase in power intensity would permit shorter ON times while lower power intensities would necessitate an increase in heat ON time. In practice there will be a lower limit to power intensity below which satisfactory ice removal would not be possible due to inadequate thermal capability coupled with inordinately long energising times. An upper limit to heater mat power intensity also exists due to heater mat thermal design and power generation considerations.

In order to comply with the ice-shedding criteria, as evolved, the heat OFF time was based on the time required to accrue sufficient ice thickness on the blade to effect clean shedding. This thickness was found, by experiment, to be of the order of $\frac{1}{8}$ inch and, because of the varying heat balance and accretion rates along the blade was not only a function of liquid water content but also of ambient temperature.

Using this procedure, systems were conveniently tested in the spray rig, liquid concentration being varied as required to cover the various design icing standards. A representative range of naturally occurring test ambient temperature could usually be obtained in the course of a winter test season. A typical example of spray rig test coverage is shown in figure 3. As a rule, stabilised cyclic de-icing operation was demonstrated by means of 30 minute test periods and the inter-cycle rotor performance degradation during operation in this manner was generally noted to be quite moderate. Traditionally this test procedure was considered admissable as formal evidence in support of applications for certification of de-icing systems for operation in natural icing conditions. Indeed, some Official Requirements specifically nominate this test procedure for certification purposes and some test programmes continue to concentrate heavily on this test method.

While the rotor performance degradation aspects were not totally ignored in this procedure, it is evident that the philosophy of operation intrinsic in the "optimum cycle time" concept concentrates particularly on the efficiency of the ice shedding process, cycle times being selected for ice removal rather than performance degradation considerations. It may be noted however, that, using the operating parameters outlined above, the frequency with which ice can be removed from the blades is given by the following simple relationship.

$$T_R = (T_{ON} \times S + T_{OFF})$$

where T_R = Ice removal period

T_{ON} = Heat ON time

T_{OFF} = Heat OFF time

S = Number of heater segments

Even with zero heat OFF time, i.e. continuous cycling, the shortest ice removal periods which can be achieved using a typical configuration (such as the Wessex) would be around 33 seconds at zero degrees centigrade increasing to nearly 4 minutes at -20°C. As already indicated, these times could only be reduced by shortening segment ON times, either by increasing power intensity or elimination of conservatism in existing heat ON time characteristics, or else by reducing the total number of segments in the cycle.

3. ROTOR PERFORMANCE DEGRADATION CHARACTERISTICS IN NATURAL ICING CONDITIONS

(a) Unprotected Rotors

Because of reliance on the occurrence of natural icing cloud, systematic testing of the effects of rotor icing on helicopter performance characteristics over the full icing envelope poses many practical problems. By the nature of things, icing severities and temperatures experienced during this type of testing vary considerably with the result that, unless one is very lucky, a very substantial volume of trials flying, utilising all available cloud, may have to be carried out in order to accumulate an adequate test sample from which to draw valid conclusions. Furthermore, when potentially limiting conditions are the subject of study, the statistically lower natural occurrence of, for example, low temperature or high severity icing conditions may result in failure to achieve the desired test coverage during the allotted trials period. Potential problem areas may therefore remain undiscovered during the development phase, possibly emerging at a much later stage during operational flying.

Figure 4 shows an envelope of resultsobtained during trials with the Lynx helicopter in natural icing conditions. While the susceptibility of helicopters to rotor icing and the performance degradation characteristics experiencedmay vary from one design to another, this summary chart does illustrate the main features which have been observed during recent icing trials.

It is now general icing trials experience that, under certain conditions of temperature and cloud liquid water concentration, many helicopters, when flown in accordance with designated trials limitations and procedures, can operate safely in icing conditions for extended periods. The trials limitations imposed usually take the form of reduced maximum forward speed envelopes, supplemented by restrictions on manoeuvre and bank angle to levels appropriate to Instrument Flight in order to provide a margin for possible performance degradation due to heavy rotor icing.

Within these limits of temperature and L.W.C., handling characteristics in all normal Instrument Flight manoeuvres, including speed changes, bank turns and entry to and maintenance of autorotation, have been found to be satisfactory. Assessment of rotor and control system monitor exceedance during such flying has also indicated that rotor system structural integrity would be unimpaired during operation of this nature. There is, however, a general increase in the torque required in flight, the level of torque rise being dependent on the icing conditions involved. Typical relationships between rotor torque and icing severity are shown in Figure 5, for substantially uniform icing conditions and in Figure 6 for variable icing conditions.

During flight in reasonably constant icing conditions, the rotor torque can be seen in figure 5 to rise over a period of a few minutes to a new, substantially steady level above datum. Constant icing conditions imply constant cloud density, constant speed, temperature and altitude and this is generally found in Layer type cloud.

More usually, the L.W.C. varies considerably in flight, due to the non-uniform composition of the cloud and the torque rise varies accordingly after a short lag as seen in Figure 6.

The torque rise experienced in flight, in addition to being dependent to some extent on natural ice-shedding and sublimation, is a function principally of temperature and liquid water content. As seen in Figure 4, the level and rate of performance degradation in high L.W.C. conditions may sometimes result in an overall torque level where it becomes prudent, and in extreme circumstances possibly essential, to vacate the icing environment. As temperatures get lower it is found that the L.W.C. associated with a given level of torque rise also reduces due to the changes in spanwise heat balance producing increased radial extent of ice and changes in the nature of the ice along the blade. At lower temperatures there is also an increased possibility of severe vibration at 1R due to asymmetric ice shedding.

Over the years these flight observations have led to the designation of two notional rotor icing envelope limits:

(i) Critical Ice Shedding Temperature

The critical ice shedding temperature, occurring around -8 to -10°C is postulated as that temperature at which spontaneous natural ice shedding, which may be contributing usefully to acceptable flight characteristics at higher temperatures, becomes progressively less effective and more erratic due to the greater adhesion of the ice to the blade and the larger masses of ice (and consequent torque rise) which must build up before self-shedding will occur. This is generally recognised as a probable lower temperature limit for acceptable operation of helicopters without rotor ice protection.

(ii) Icing Threshold Temperature

This limit, related to the "Kinetic Heating Effect" stems from the heat balance situation along the blade. Messinger's classic theory (Reference 2) predicts that the Kinetic heat rise and freezing fraction effects result in the blade leading edge stagnation temperature being above zero over aerodynamically significant outboard portions of blade at ambient temperatures below zero down to approx. -5°C as shown in Fig.7. It is apparent that this result can be considerably influenced by the presence of varying amounts of water and, also, that, in this elementary calculation from the theory, no account is taken of subtleties of heat balance which may occur away from the stagnation point. However, the potential benefits of this temperature rise are clear since the formation of ice on critical outboard portions of the blade could be effectively delayed to ambient temperatures below the operationally and statistically relevant high sub-zero temperature range. Kinetic heating, therefore, had come to be relied upon as a justification for Icing Release with unprotected rotor systems down to -5°C and also as the basis for a general design dogma that rotor ice protection was not required above this temperature.

Unfortunately, a number of recent trials experiences in high sub-zero icing conditions have given cause to question the adequacy of the heat balance theory. For example, Fig. 8, taken from Reference 3, shows a time history of rapid degradation in performance during flight in severe icing conditions at -3.5°C, on a Wessex 5 helicopter during trials carried out by a British M.O.D. team in Canada. Similar characteristics have been observed on the Wessex on a number of other occasions. It is of interest to note that, as related in Reference 3, photographic evidence has also been obtained confirming ice accretion out to at least the 90% blade radius station during flight in the -2°/-4° temperature band. As yet, no satisfactory theoretical explanation for the apparent disparity with the Messinger result has been developed although it has been conjectured that an additional 'cold' source imput into the heat balance in the form of, say, ice particles, possibly a consequence of 'mixed conditions' might have been responsible. Although no flight occurrences of such severity in this temperature band have been reported so far on other helicopters there is now evidently a need to interpret this area of the icing envelope with increased caution.

Of particular note in Figure 8 is the rapidity with which the condition deteriorates, the significant time for this sequence being 20 to 30 seconds. The increases in torque and collective pitch required, the loss of altitude and airspeed and the development of rotor blade stall symptoms and attendant control and fatigue issues evident in the increased oscillatory control load characteristics are all factors which, with such a critical time element, have important implications on the practicability of supporting continued flight in the icing environment by means of cyclic blade de-icing systems.

(b) Protected Rotor Systems - Cyclic Blade De-Icing

From consideration of the performance degradation characteristics experienced with unprotected rotor systems, two basic operating regimes for rotor ice protection systems can be identified:

i Non-critical icing regime

ii Critical icing regime

The non-critical regime is that area of the icing envelope within which, as discussed in section 3 (a), helicopters have frequently shown signs of being capable of operation for extended periods without rotor protection, albeit also subject to some flight restrictions and residual performance penalties due to the increased torques required in flight. The critical icing regime is the area outside the non-critical icing envelope.

While rotor protection may not be essential within the non-critical area, there are benefits to be gained by keeping the blades as free of ice as possible. For example, a well-matched cyclic ice removal sequence can confer significant reductions in the mean level of the torque rise, while periodic 'cleaning up' of the blades, aerodynamically, may give increased confidence during prolonged flight in icing conditions since a continuing build-up of ice over the rotor system as a whole will be checked. Some relaxation of flight speed and other restrictions could also be possible due to the reduced probability of premature blade stall and damaging oscillatory stresses in the dynamic system. However, the main feature of this area of the icing envelope is an inherently low probability of experiencing levels and rates of performance degradation which might require either immediate vacation of the environment during flight without rotor protection or, alternatively, urgent and frequent removal of ice from the rotor blades during operation with cyclic blade de-icing protection. Because of the relatively moderate rates of performance loss encountered in this area, it will not generally be necessary for the timing of a de-icing cycle to be critically related to the helicopter performance situation although it is very desirable that the cycle should be well-matched at all times.

The definition of the limits of the non-critical area of the icing envelope in terms of ambient temperature, altitude and icing severity, and the formulation of suitable operating limitations and procedures requires a considerable knowledge of the icing tolerance of the helicopter concerned and this knowledge must be carefully interpreted in relation to the operating spectra and statistical icing severity probabilities. At the current state of knowledge, it would appear that, in general the practical limits of non-critical icing lie somewhere between 'moderate' and 'severe' icing (day, 70-100% of the current Continuous Maximum Design Standard Icing Condition) down to -8° to -10° Centigrade. Because of the potentially hazardous levels of degradation which may occur outside these limits, it becomes necessary to provide some form of positive rotor ice protection to support sustained flight in such conditions, and to reduce substantially the probability of having to make an enforced exit from cloud.

Very little has been published on the operating characteristics of cyclic blade de-icing systems in natural icing conditions and the remarks which follow are based largely on experience gained during experimental trials carried out with the Westland/Lucas development blade de-icing system. There are, however, a number of similar programmes in progress elsewhere (for example References 4 and 5) and it is hoped that, in due course, further knowledge will become available in order to make a wider interpretation possible.

As usual in natural icing work, there are frequently difficulties in obtaining the required test conditions. Figure 9 illustrates the type of coverage which may result from typical icing trials flying during which the tests have to be arranged on an oportunity basis. Generally speaking, a large proportion of naturally occurring icing cloud is of only light to moderate severity and therefore of relatively low significance in relation to the probable performance limits of a blade de-icing system. However, the maintenance of a clean and effective ice removal process continues to be important since gross mismanagement of a cyclic heading cycle could possibly result in parasitic performance degradation due to the formation of runback ice.

In the course of investigatory work with the Wessex de-icing system, potentially critical conditions have been encountered on a number of occasions as indicated in Figure 9. Four cases have occurred at temperatures below the so-called critical ice shedding temperature while characteristics similar to those depicted in Figure 8 have been encountered at high sub-zero temperatures on two occasions.

Although the design of current blade cyclic de-icing systems continues to follow the broad principles outlined in Section 2, most development systems now usually incorporate variable cyclic parameter functions, tacitly admitting a possibility that the 'optimum cycle' may have to be adjusted in the light of trials results. During trials, a variety of approaches to the use of the variable parameters have been tried:

1. OFF TIME

(a) OFF time modulated in accordance with the output from an ice accretion/severity signalling system.

(b) Continuous cycling i.e. Zero OFF time

(c) Manually set OFF times of 2-3 minutes

(d) Cycle initiated on demand as required by the flight circumstances

2. ON TIME

(a) Automatically - controlled, as a function of ambient temperature (e.g. Figure 2)

(b) Manually selected ON time

1(a), 1(b) and 1(c) in conjunction with 2(a) can, in principle, provide an automatic, self-operating, cycle while the 'On Demand' systems 1(d) in conjunction with either 2(a) or 2(b) require to be closely monitored by the flight crew. A manually initiated cycle is very useful during cycle development work but the aircrew workload involved would normally be unacceptable for in-service I.F.R. operations.

From consideration of the icing characteristics observed in flight, it is evident that a highly adaptive control and signalling system must be available if fully automatic cycling is to cope successfully with the wide range of icing conditions which can be encountered.

During trials, all of the foregoing methods have, on occasions, successfully promoted ice shedding from rotor systems, enabling continued flight for extended periods. However, none have so far demonstrated an inherent capability of supporting satisfactory operation for all flight circumstances. For example, OFF times of 2 or 3 minutes could clearly be unsatisfactory in the rapid torque rise situations illustrated in Figure 8, while even with near-zero OFF times, the re-accretion which sometimes occurs during the de-ice cycle may, on occasion, be excessive, requiring shorter overall cycle times in order to prevent the de-ice cycle from being 'overlapped' by further performance degradation.

Figure 10 shows typical de-icing system operation during manual initiation in response to observed fairly rapid and high torque increases at -2/-3°C. It may be seen that, even with a total de-icing period of only 1½ to 2 minute, substantial torque increases of 700 to 800 LB.FT. can occur. While a zero OFF time and some reduction in heater element ON times (provided these do not interfere with the efficiency of ice shedding) could reduce this significantly, it is apparent that in this instance, major torque increases are occurring in around 20 seconds, which is rather less than the response time of the reference ice detector counts shown and also faster than many designs of fuselage-mounted cyclic accretion-type ice detectors. The automatic initiation of cyclic de-icing functions in this situation therefore poses some signalling and control logic problems.

Also apparent in Figure 10 is the rise and fall of the stationary and rotating star oscillatory control loads during ice accretion and shedding. Of particular note is the marked reduction in stationary star load at de-ice cycle switch positions 1 and 6. These switch positions relate to the switching of the loading edge heater mats on the first and second pairs of blades respectively (ref, Fig. 1). It must be remembered, however, that the stationary star control load is a function of the control loads of all blades in the rotor system and this characteristic may sometimes be masked by the combined effects of accretion and shedding in a 'paired' blade situation. The behaviour of the rotating star control load is more distinctive and exhibits a sharp reduction in magnitude at switch position 6, the rotating star control load recorded being one of the second pair of blades in the cycle.

The control load behaviour during ice shedding is illustrated in greater detail in the sample of trace record shown at figure 11. This clearly shows a significant reduction in amplitude, and suppression of a wave form spike (attributable to premature, ice-induced, blade stall), implying leading edge ice shed within 1½ seconds of the leading edge heater mat being energised. Detailed study of the trace waveforms also confirmed a reversion to the 'clean blade' characteristic immediately following this event.

Similar effects have been observed at lower temperatures (-8°to -12°C) but generally with a somewhat longer time factor. For example, in low to moderate icing severity and cyclic de-icing in continuous operation, (i.e. zero OFF time) giving an ice removal period of between two and three minutes inter-cycle mean torque increases of the order of 500 LB.FT. have been observed. Such increases, although not critical in a general context, are judged to be undesirably high for routine operation. This situation arises primarily because of the increase in the radial extent of ice on the blades as temperature reduces. Outboard ice, being at a local temperature which may be somewhat above ambient, also tends to be of horned, glaze type which is particularly damaging in terms of aerodynamic performance. In higher icing concentrations, or on transition from low to high icing severity, the rate of degradation will increase considerably, resulting, again, in a need for rapid, urgent, cyclic de-icing.

To summarise, during operation in critical icing conditions, a cyclic blade de-icing system is liable to two critical requirements:

(i) Provision of a rapid, and frequent, ice removal capability.

(ii) Provision of almost immediate, severity-related, cycle initiation signalling during high rates of performance degradation.

It is now clear that, during operation in critical conditions, it may become necessary to modify substantially, or even abandon, the classic heater ON and OFF time relationships associated with the 'optimised cycle'. To date, there is no evidence that such action has significantly affected the quality and efficiency of ice removal or that it has been the cause of parasitic performance degradation due to runback refreezing. However, experience of cyclic de-icing system operation in critical icing conditions is limited and the deviations from the 'optimised' cycle have been relatively moderate. There is now increasing evidence that future cycle changes may have to be more drastic if satisfactory operation in critical natural icing conditions is to be achieved. In such circumstances it will be essential to monitor the effects of such changes on the ice removal characteristics very closely.

4. DEVELOPMENT POSSIBILITIES

From the foregoing, it is evident that there is now a need to speed up both the initiation signalling and the de-icer functioning. This can only be achieved by adjustments within the de-ice cycle itself or by reappraisal of the ice shedding and protection sequences employed.

A very wide range of changes can be devised. However, exhaustive study of all of these is outside the scope of the present discussion and the basic categories of possible system changes will therefore be considered in broad outline only.

The first, and perhaps most obvious, method of speeding up the ice removal process is by making adjustments within the present cycling sequence - reducing the number of de-icing steps in the cycle or by reducing the energising or heat ON time. Initially this can be tackled by ensuring that heat ON time is just sufficient to effect ice removal. It is also most important that the overall cycle should not be lengthened unnecessarily through retention of protection on non-critical surfaces. Evaluation of this aspect is understood to have been carried out during testing of the BO 105 system in the Spray Rig at Ottawa (Reference 4). Once the ON times and protected surface areas have been reduced to acceptable minima, further reduction in the total cycle time can be achieved either by increasing the areas of the individual segments, thus reducing the number of steps; or by increasing power intensity to reduce the ON time further. Unfortunately, both courses of action could incur a significant increase in the power required. The power generation requirement can be eased somewhat by using a power generation system 'rating' philosophy in which high alternator ratings and increased heater mat power intensities are used only during conditions of high icing severity or at low temperatures when there is a need for the shorter cycling times which become available with high heater mat power intensities. Because of the relatively low statistical occurrence of critical icing 'short duration' alternator rating philosophies can be accommodated in the machine life substantiation. A fuller description of this approach can be found in Reference 5.

Throughout this paper, a spanwise (chordwise shedding) segmental arrangement has been assumed for illustrative purposes. However, chordwise (spanwise shedding) segmental arrangements are also in use, each approach having its own particular advantages and disadvantages.

In the context of the ice protection performance afforded by each category of system there is no evidence at the present time identifying a preferred arrangement and the foregoing discussion on rotor protection in critical conditions applies equally to both configurations.

In the event of an 'Optimised' or uprated classic system proving inadequate to achieve the desired performance capability in severe icing conditions, recourse might have to be made to a variety of 'compound' cycling and 'hybrid' mixed anti-icing/de-icing systems.

The concepts of compound and hybrid systems are based on the premise that heavy rotor performance degradation is associated predominantly with leading edge ice accretion and/or large accretions on the outboard 30-35% of blade. It is now well known that even quite small amounts of roughness on the leading edge of an aerofoil can have a very substantial influence on the lift, drag and stalling characteristics of an aerofoil, while the contribution of the outboard portions of blade to rotor performance characteristics is readily demonstrated by means of rotor theory. It could therefore be beneficial to accord preferential consideration to such areas of the blade during the design of the ice protection sequences.

In a 'compound' cycling system, selective repeat cycling of leading edge, or outboard, areas of the blade could be injected approximately midway through the cycle such that, in principle, peak ice accretions in these areas would by substantially reduced giving corresponding reductions in the performance degradation.

A hybrid mixed anti-icing/de-icing systems would embody controlled continuous heating of selected critical leading edge or outboard areas of the blade - other areas would continue to be de-iced cyclically as before. This approach requires very careful thermal control and de-icing timing if the generation of serious runback ice, particularly with continuous leading edge heating, is to be prevented. Continuous heating outboard, if properly controlled, could be used to advantage to augment the natural kinetic heating effect already discussed.

The primary objective of both categories of system would be to obtain a substantial alleviation of the stringent de-ice time factor intrinsic in classic de-icing systems as traditionally conceived. Such systems could not only reduce the critical nature of the cyclic timing required but could also contribute, eventually, to a simplification of theice detection and control signalling logics required. Unfortunately, although the power intensities required for anti-icing are substantially lower than the levels used in de-icing, the introduction of even quite modest areas of continuous anti-icing heating on blades is likely to require a considerable increase in power.

5. CONCLUSIONS

In this paper an attempt has been made to review the characteristics of rotor blade ice accretion and rotor performance degradation in the light of practical trials flying with protected and unprotected rotor systems in natural icing conditions.

A non-critical area of theicing envelope has been identified within which safe operation with unprotected rotor systems could be possible subject to appropriate flight precautions and limitations and positive ice protection systems could be expected to permit a relaxation in flight restrictions and increased confidence during extended operation.

Rotor de-icing system operating characteristics in natural icing conditions have been examined and it is concluded that the simple, classic, ice-shedding criteria evolved during spray rig testing are inadequate to support satisfactory operation in critical icing conditions. A major review of ice removal patterns will be required, and revised ice protection sequences evolved in order to meet requirements for fully automatic system operation in potentially critical icing conditions.

6. REFERENCES

1. J.R. Stallabrass, Canadian Research in the Field of Helicopter Icing
J. Helicopter Association of Gt. Britain.
Vol. 12 May 1958.

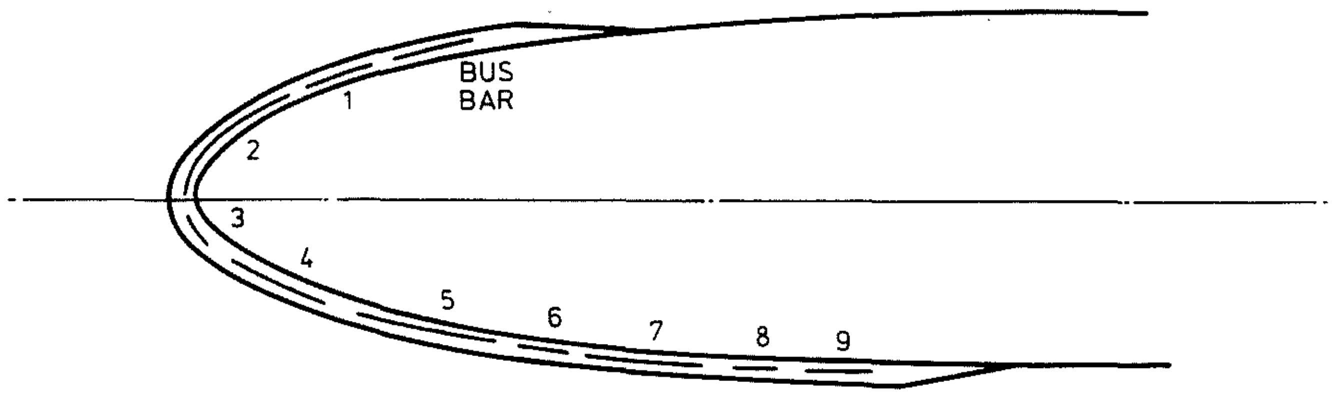
2. B.L. Messinger, Equilibrium Temperature of an Unheated Icing Surface as a function of Airspeed.
Journal of Aeronautical Sciences.
Vol 20, No,1, 1953.

3. H.B. Lake and J. Bradley, The Problem of Certifying Helicopters for Flight in Icing Conditions.
Royal Aeronautical Society Symposium -
"Icing on Helicopters" 26th November 1975.

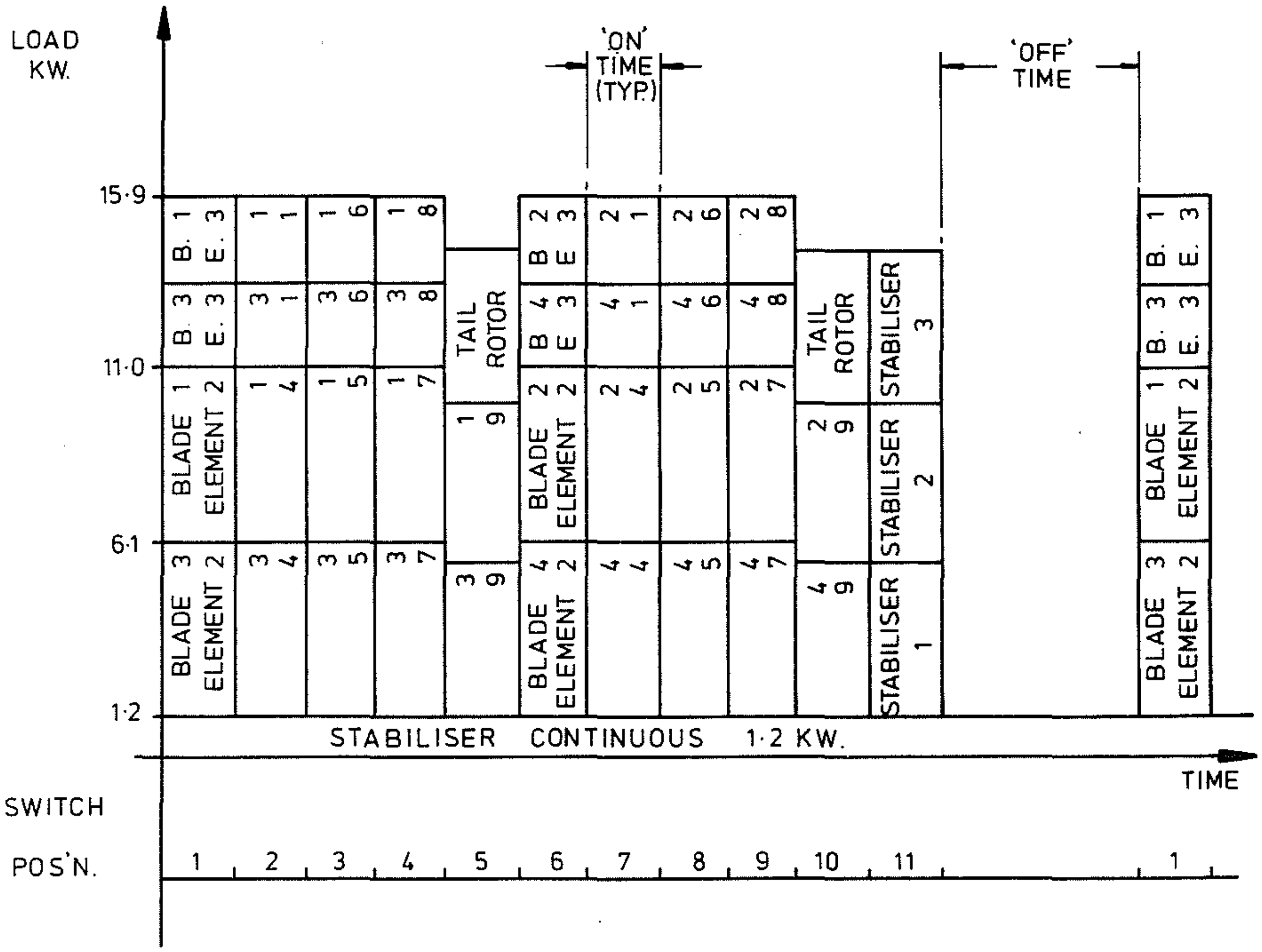
4. A.J. Horlebein and H. Melcher, The BO 105 Ice Protection System.
Rotary Wing Icing Symposium.
Edwards AF.B. 4th-6th June 1974.

5. J.B. Werner at Al, *The Development of an Advanced Anti-Icing/De-Icing* Capability for U.S. Army Helicopters
Vols. 1 and 2 USAA MRDL-TR-75-34B,
November 1975.

The views expressed in this paper are those of the author and do not necessarily represent the views of Westland Helicopters Limited.



MAIN ROTOR BLADE - HEATER ELEMENTS.



CYCLIC SWITCHING SEQUENCE.

FIG. 1. TYPICAL ROTOR DE-ICING PROGRAMME - WESTLAND / LUCAS DEVELOPMENT SYSTEM

WESSEX ~ HEATED ROTOR BLADE SYSTEM

DE-ICE CYCLE TIME ~ AMBIENT TEMPERATURE

(NOMINAL DESIGN AUTOMATIC MODE, 11 SWITCH SEGMENTS)

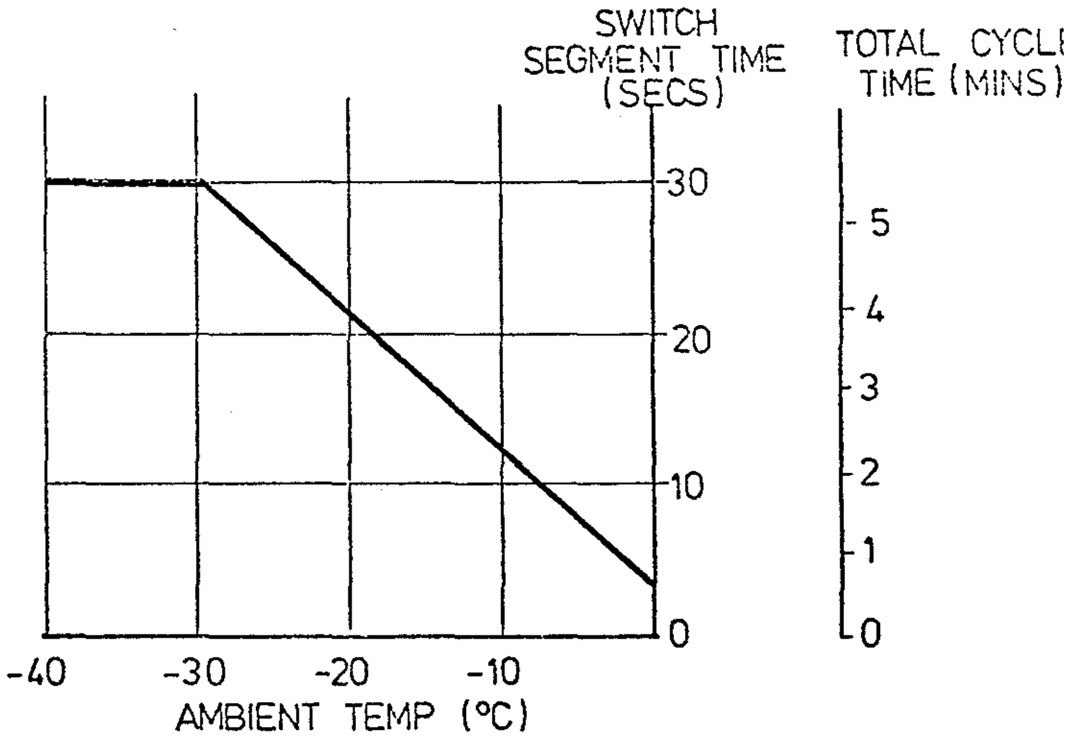


FIG. 2

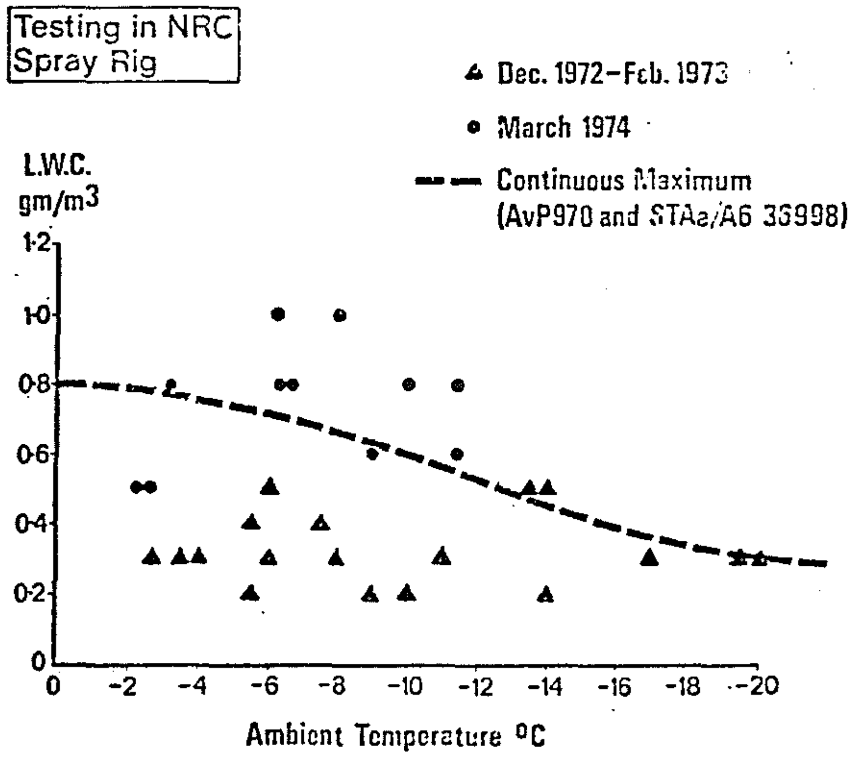


Fig. 3. Wessex - Heated Rotor Blade System

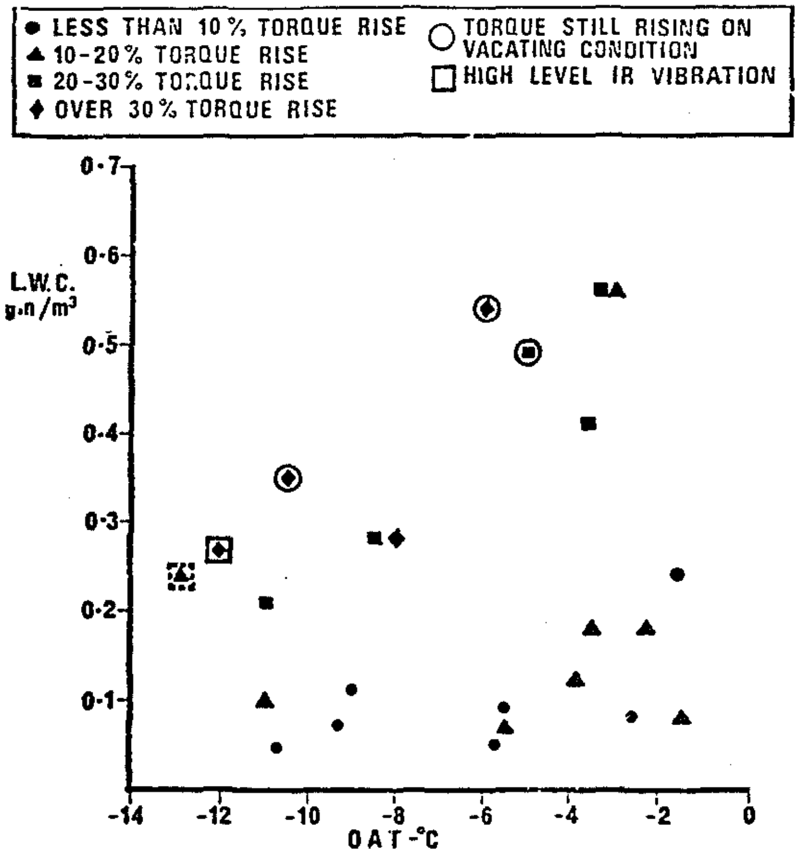


Fig. 4. Lynx - Graph of L.W.C. + O.A.T. Showing Torque Rises Experienced in Natural Icing Conditions.

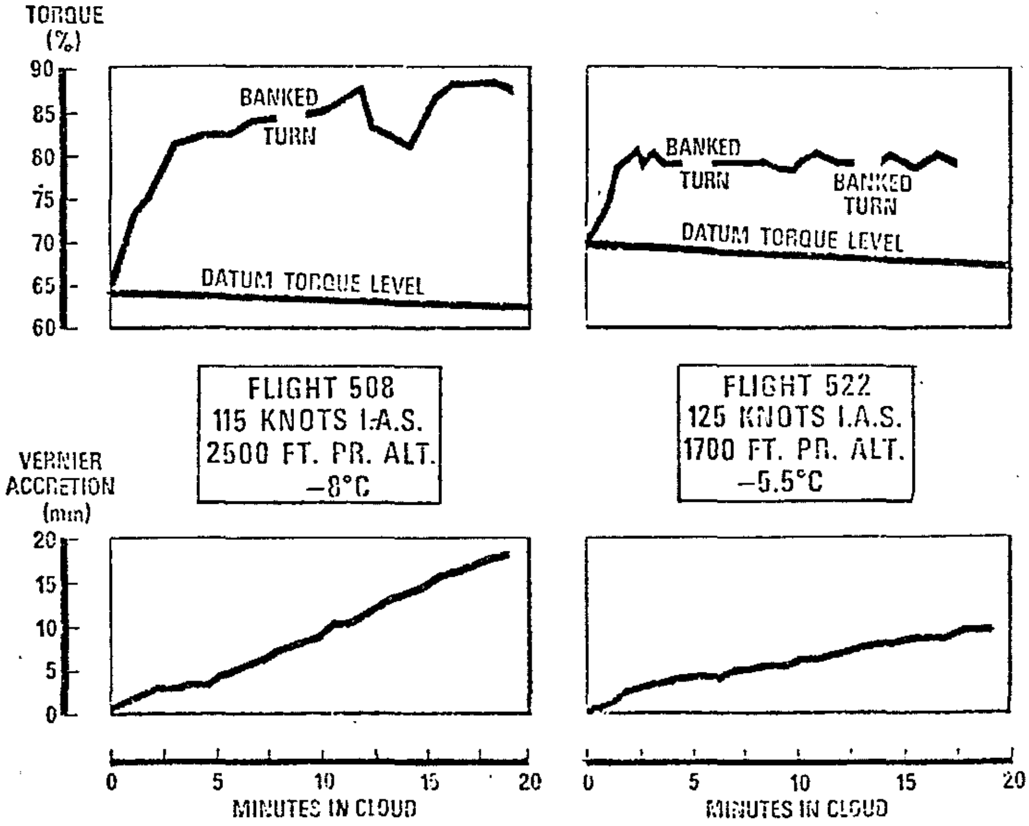


Fig. 5 Lynx - Typical Flights in Consistent Icing Conditions

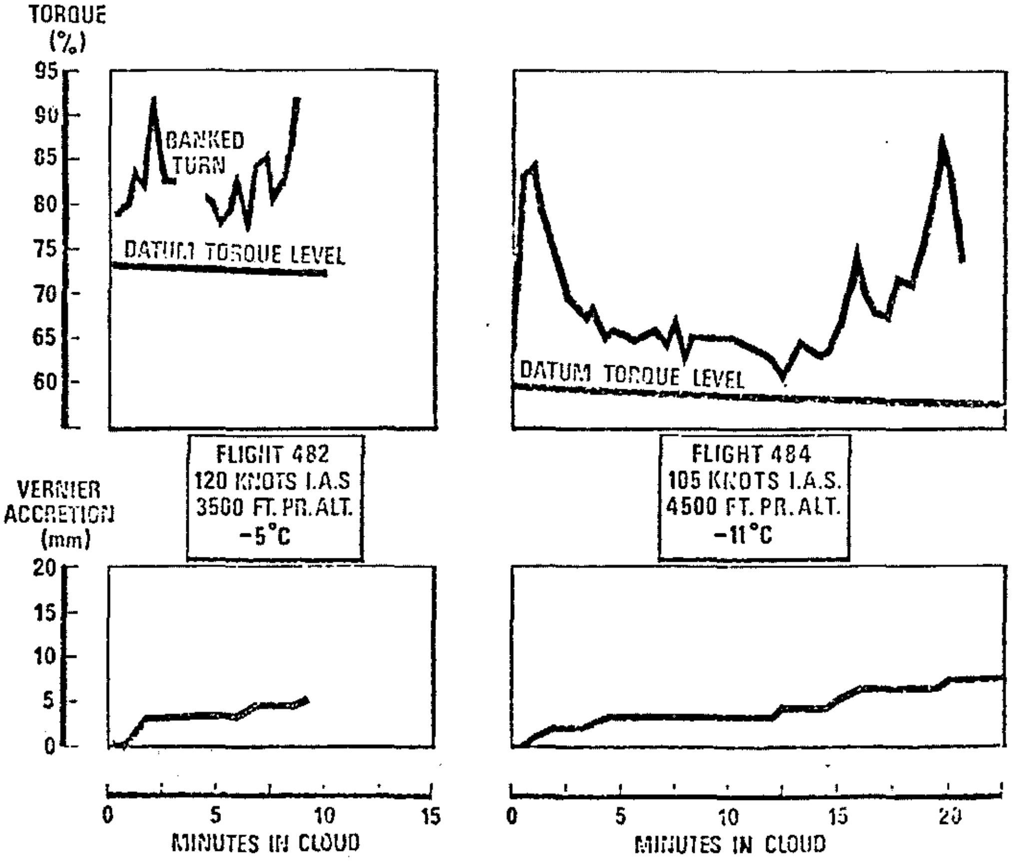


Fig. 6 Lynx - Typical Flights in Variable Icing Conditions

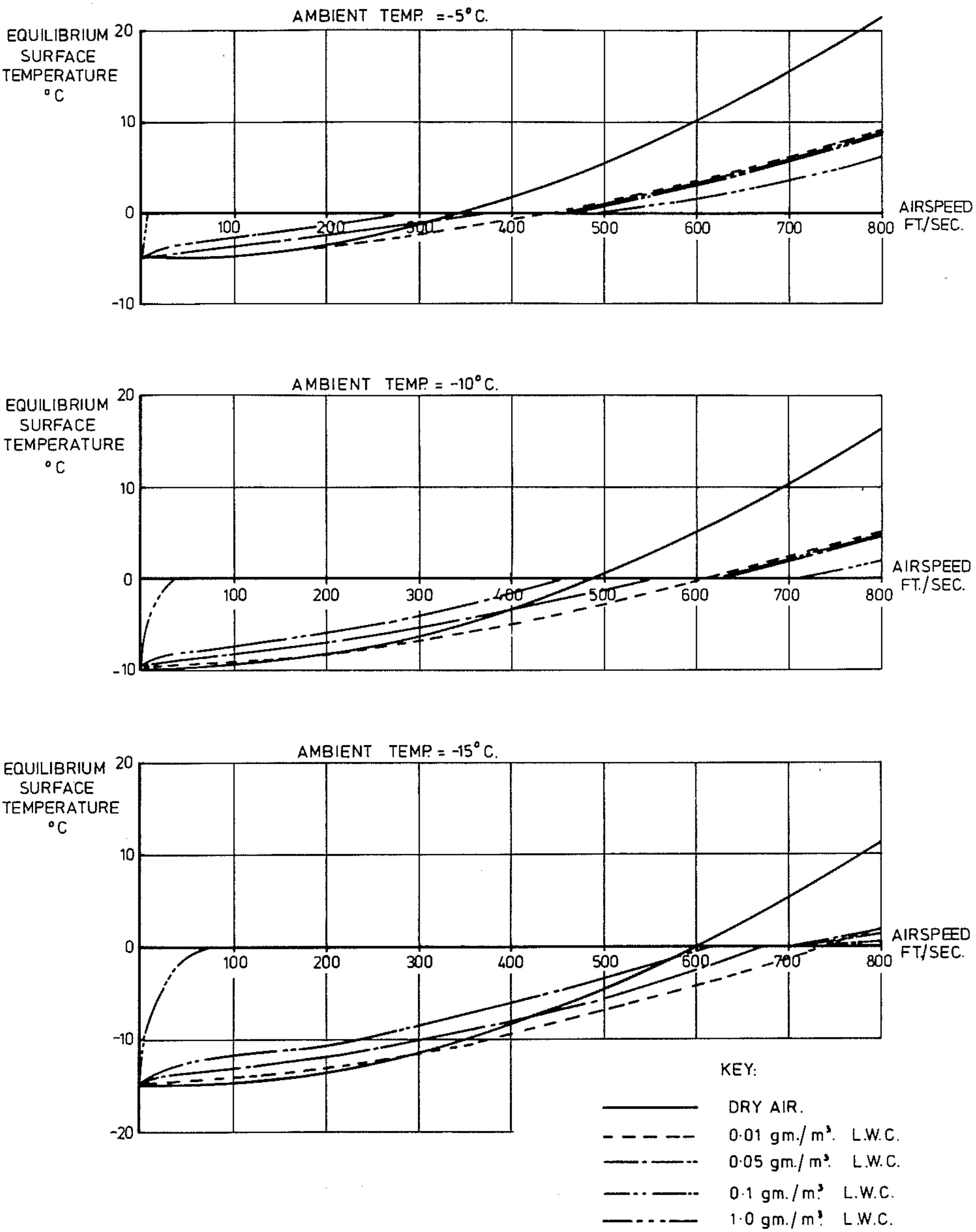


FIG. 7. ROTOR BLADE LEADING EDGE STAGNATION TEMPERATURE. (AFTER MESSINGER)

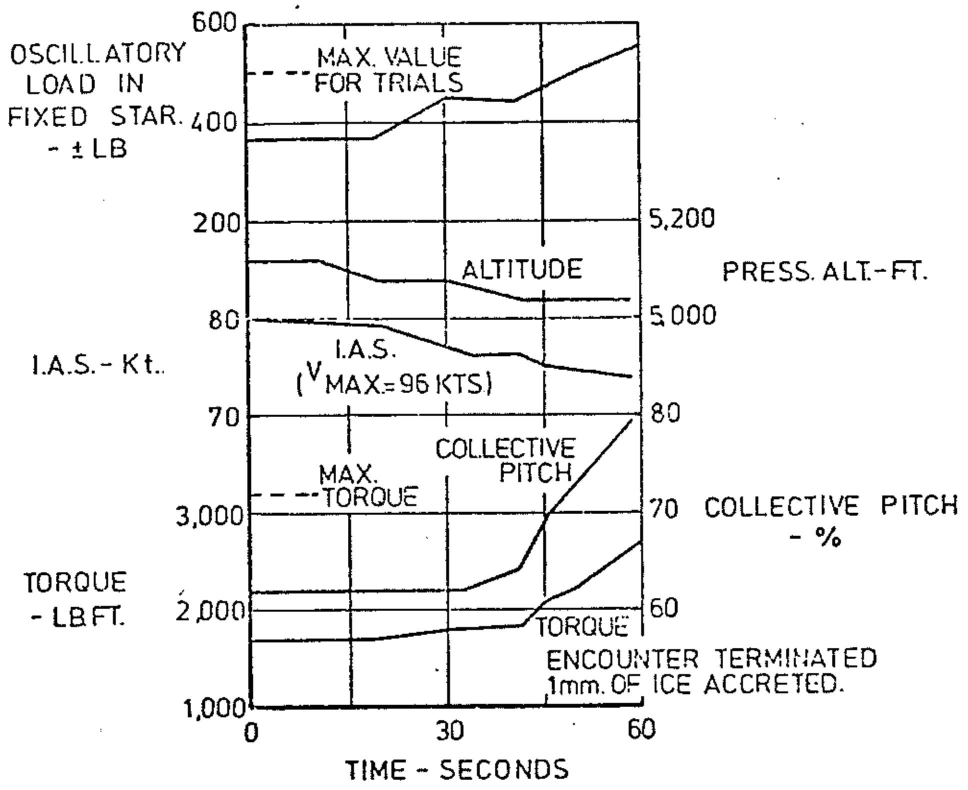


FIG. 8. RAPID ONSET OF ROTOR ICING O.A.T. -3·5°C. ~ WESSEX 5.

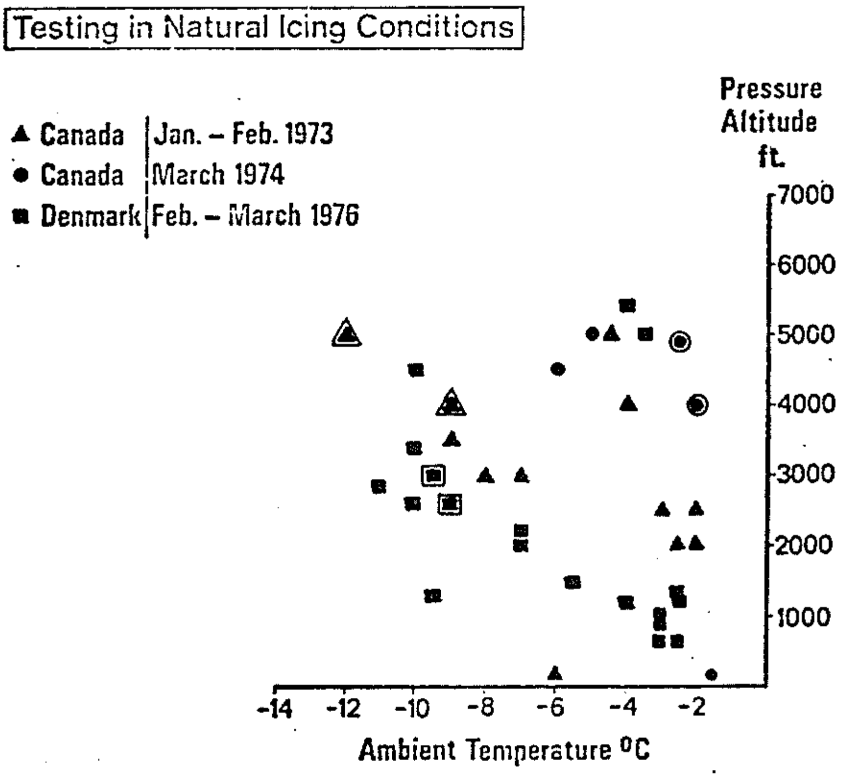


Fig. 9. Wessex - Heated Rotor Blade System

WESSEX HEATED ROTOR BLADE SYSTEM
4900 FT PRESSURE ALTITUDE
80 KTS IAS
-2°/-3° C AMBIENT TEMPERATURE

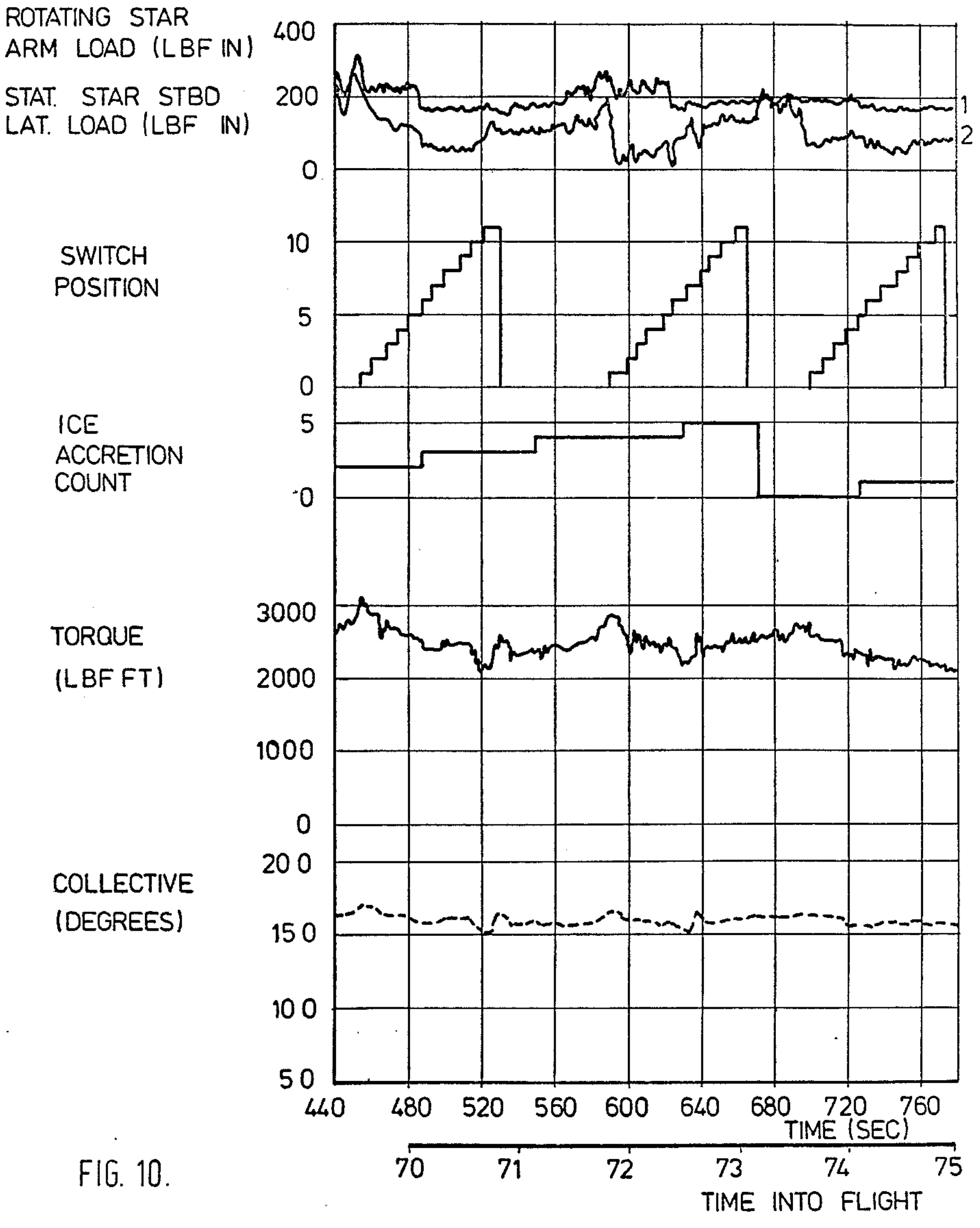
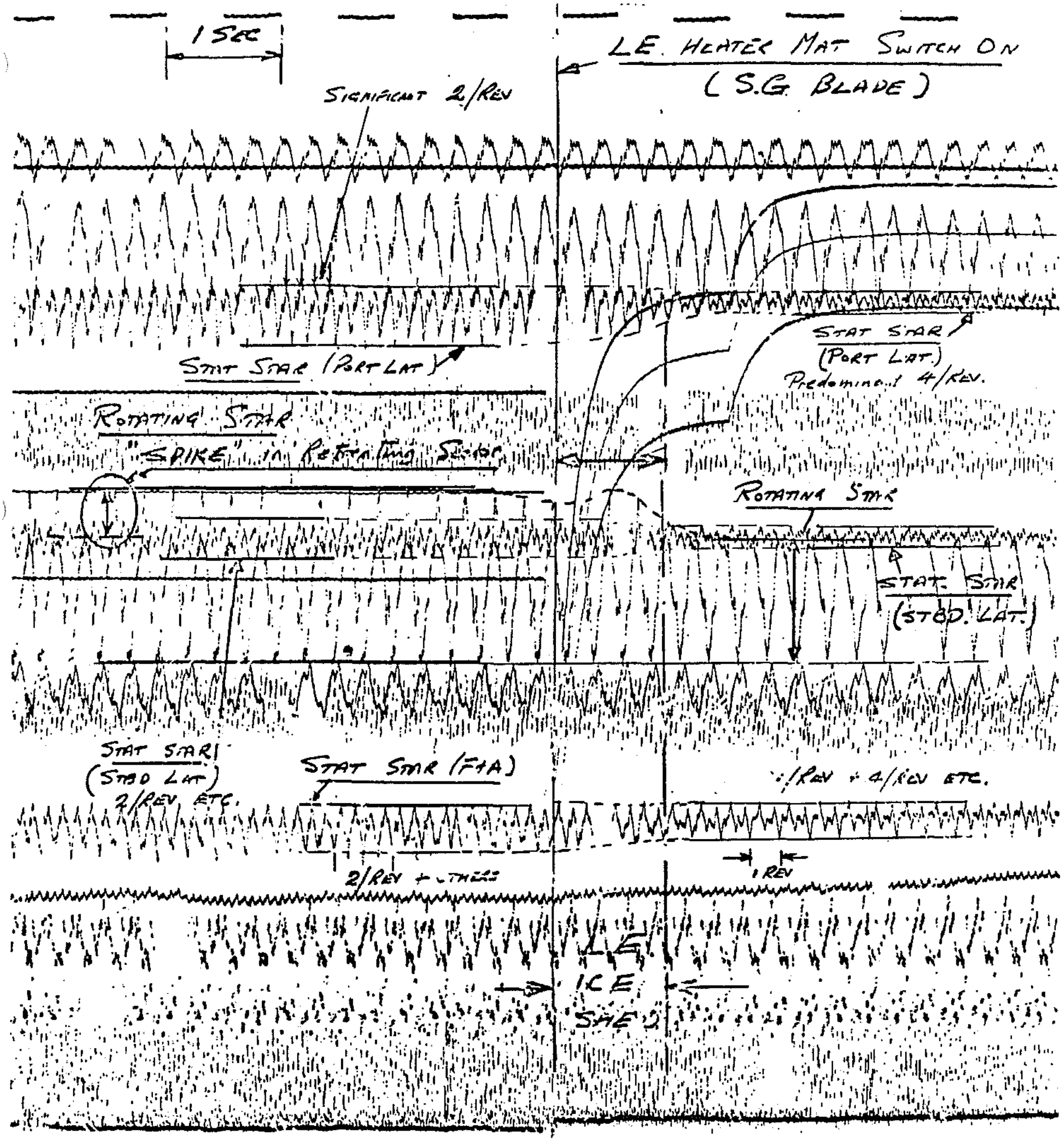


FIG. 10.



TYPICAL CONTROL LOAD HISTORY – L.E ICE SHED

WESSEX HEATED ROTOR BLADE SYSTEM

FIG. 11