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NATIONAL RESEARCH LABORATORIES

Ottawa, Canada

REPORT

Division of Mechanical Engineering

Low Temperature Laboratory

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Subject: A COMPARISON BETWEEN THE SPANWISE AND CHORDWISE SHEDDING METHODS OF HELICOPTER ROTOR BLADE DE-ICING.

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SUMMARY

Flight tests in an artificial icing cloud were made on two sets of helicopter rotor blades equipped with de-icing heater mats embodying the spanwise and chordwise shedding principles. The tests demonstrated a decided performance advantage for the spanwise shedding system, although the chordwise shedding system had the advantage of greater constructional simplicity.

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A COMPARISON BETWEEN THE SPANWISE AND CHORDWISE SHEDDING METHODS OF HELICOPTER ROTOR BLADE DE-ICING

1.0 INTRODUCTION

Previous theoretical and practical work (Ref. 1 and 2) has indicated that the spanwise system of electro-thermally shedding ice from helicopter rotor blades has some distinct advantages over the chordwise shedding system. The "spanwise shedding system" is defined as the one in which the heater element is disposed on the blade in a number of adjacent chordwise areas which are activated in a spanwise sequence starting from the tip (Fig. 2); while in the "chordwise shedding system", the heated area is comprised of spanwise strips which de-ice in a chordwise sequence starting from the leading edge (Fig. 3). A direct comparison between the two methods was necessary to verify the earlier findings and to determine whether the advantages were sufficient to warrant the extra manufacturing and installation difficulties of the more complex spanwise shedding elements.

Accordingly it was decided to construct two sets of main rotor de-icing elements for a Bell 47-type helicopter. Except for the disposition of the heated areas, the heater mats were of identical construction and coverage. The heating element was made of woven wire sandwiched between insulating layers of resin, and the complete heated area was covered by a stainless steel abrasion shield.

Flight tests on the first set of blades (i.e. the chordwise shedding system) were begun under simulated icing conditions in the first week in February, 1959. Because of exceptionally fine weather conditions, almost all of the complete schedule of test was finished by the end of the winter season despite the late start. The few tests not completed on the chordwise shedding blades were the result of a manufacturing flaw which precipitated a burn-out of the connections to one of the heater elements (see Appendix A).

2.0 PURPOSE

The purpose of the tests was to compare directly the relative effectiveness and efficiencies of the spanwise and chordwise methods of shedding by flight testing similarly constructed examples of each system over the same range of ambient conditions and at the same specific power densities.

3.0 TEST EQUIPMENT

3.1 Aircraft

The aircraft used for all trials was a Bell 47-J helicopter (Fig. 1). The leading particulars are as follows:

Engine

Type	Lycoming Vo435 A1B
Maximum power	240 h.p. at 3100 r.p.m. and 27 in. Hg manifold pressure
Main rotor/engine speed ratio	1/9

Main Rotor Blades

Type	H 13-H metal blades
Rotor diameter	35 ft. 1½ in.
Blade chord	11 in.
Blade aerofoil section	NACA 0015

For all test flights, the aircraft was flown at a gross weight of about 2300 lb. and an engine speed of 3000 r.p.m.

3.2 De-Icing Heater Mats

The heater mats were built up directly on the basic metal structure of the rotor blades. The construction of these mats was as follows:

Material	Thickness (in.)
Base insulation and adhesives	0.018
Goodyear heater element	0.018
Outer insulation and adhesives	0.008
Abrasion cap - copper-clad stainless steel	0.006 (s.s.) 0.010 (cu)

The layout and dimensions of the spanwise and chordwise shedding mats are shown in Figures 2 and 3 respectively and the electrical data are shown in Appendix A.

The heater elements were made of nichrome wire woven in glass cloth at a density of 48 wires per inch. In the chordwise shedding elements the wires ran spanwise and the four 155-in. long by 1-in. wide heated strips were made up of two $\frac{1}{2}$-in. passes so that all connections were made at the root end. In the spanwise shedding elements, to minimize cold spots, the wires ran chordwise with connections being made to each of the five $30\frac{1}{2}$-in. long by 4-in. wide areas by means of resin covered flat leads running along the blade immediately aft of the heating elements.

All areas on both types of elements were designed for normal operation at a uniform power density of 30 watts/sq. in. with an input voltage of 180 volts; however, the elements were capable of operating at 40 watts/sq. in. without deterioration.

On both sets of blades the mats had a chordwise coverage of 10 percent on the upper surface and 26 percent on the lower. The spanwise coverage on the spanwise shedding blades was from the tip to about 29 percent span (Sta. 61) and, on the chordwise shedding blades, from the tip to 27 percent span (Sta. 57).

Because of manufacturing difficulties in applying the spanwise shedding heater mats, the experimental blades were aerodynamically rough. There were small creases in the stainless steel abrasion cap along the leading edge and roughnesses in the resin coverings over the busses and leads on the top and bottom surface of the blades. These latter can be clearly seen in the top view in Figure 18. These imperfections resulted in restrictions to the maximum airspeed and rate of climb for the aircraft but did not affect the hovering tests.

3.3 Power Supply

The electrical power for energizing the heater elements was supplied from the ground, through a variable voltage transformer, a trailing cable, slip rings and a selector switch system.

The supply was single phase, 60 c.p.s. at a voltage of 220 volts. Power density of the heater mats was varied by adjusting the voltage of the supply to the aircraft by means of the variable transformer. Voltage settings and current flows were metered both on the ground and in the aircraft. Correction was made for the voltage drops in the cable and slip rings.

The trailing cable was 200 ft. in length and could be released from the aircraft by means of a modified bomb release. A weak link was also provided which released the cable should the pull on it exceed 100 lb.

By means of a control box in the cabin (Fig. 4) and a selector box mounted on the main rotor mast above the slip ring/swash plate assembly (Fig. 5), any heater mat or symmetrical pair of heater mats could be energized individually or sequenced automatically. Automatic sequencing could be effected either symmetrically or alternately at any pre-set on-time from $\frac{1}{2}$ to 60 seconds in $\frac{1}{2}$-second steps.

3.4 Instrumentation

A photo observer panel was mounted in the aircraft cabin (in background in Fig. 4) to record engine and flight data, including outside air temperature and signals from an icing detector.

The icing detector was of the twin probe orifice type, with the reference and sensing probes mounted in opposite ends of the rotor stabilizer bar, and a differential pressure switch at the rotor hub.

3.5 Spray Rig

The spray rig described in Reference 3 and shown in Figure 6 was used to produce the icing cloud. Instrumentation at the test site measured windspeed, temperature and humidity.

3.6 Miscellaneous

Contact was maintained between aircraft and ground by an intercommunication cable attached to the trailing power cable and connected into an amplifier in the test hut.

Correct location of the helicopter in the cloud at a given distance from the spray rig was aided considerably by spraying patches of sea marker dye in suitable locations on the snow covered ground. This was particularly helpful on dull, overcast days when there was little contrast between ground, sky and artificial icing cloud.

4.0 TEST PROCEDURE

On each flight the helicopter was hovered in the simulated cloud about 100 ft. downwind from the spray rig and enough ice accreted on the rotor blades to facilitate efficient shedding without overly jeopardizing helicopter performance. From past experience with the cloud it was known that a suitable thickness of between 1/8 in. and 1/4 in. (Ref. 2) would be picked up in about 4 minutes in moderate icing conditions. When sufficient experience with the ice detector had been gained, its rate of signalling was also used as an indication of the amount of ice build-up on the rotors.

When enough ice had been accreted the helicopter left the cloud and hovered in clear air where a de-icing cycle at some pre-set power density and on-time was initiated. (Periodically the aircraft was landed before de-icing to verify that a suitable thickness of ice was being picked up on the rotor blades.) After de-icing, the aircraft was landed and the rotor stopped so that the extent of shedding could be inspected. If complete shedding had not been accomplished the blades were cleaned and the run was repeated at longer on-times until a complete shedding point was found. Conversely, if the first cycle resulted in complete shedding, the run was repeated at shorter on-times until shedding was incomplete. This method gives a number of good and bad shedding points such that, when plotted, the mean line between them compensates for inconsistencies in shedding energy caused by variations in accretion thickness and represents the optimum operating conditions.

De-icing was usually performed in clear air rather than in the cloud. This presented the more severe case since the ice temperature under clear air conditions would have been close to ambient, whereas in the cloud it would have been nearer to 0° C and dependent to a large extent on the value of liquid water content; thus this variable was removed from the shedding performance. It is desirable to design for this condition of clear air shedding to cope with the case of shedding after emerging from an icing encounter.

A few flights were made to determine the performance of the system when de-icing in the cloud, including a single icing and de-icing cycle run with correct on-time, and extended runs using both correct and excessive on-times.

Power densities of 20, 30 and 40 watts/sq. in. were used. Generally shedding was performed symmetrically from both blades, although on a few occasions with the spanwise shedding mats, alternate blade de-icing was tried to assess its feasibility.

5.0 TEST RESULTS

5.1 General

Test flights were performed on a total of 13 days between 7 February and 8 March, 1959. Of these, 8 days were taken for 42 individual flights with the chordwise shedding blades and 5 for 49 flights with the spanwise shedding blades. Each flight consisted of a complete cycle of icing and de-icing with occasional landings between the two to measure the ice accretion.

The tests were conducted over a range of ambient temperatures from -6.3°C to -22.9°C and liquid water contents from 0.08 to 0.35 gm./m^3 The droplet size was kept constant at about 30 microns (median volume diameter). The test conditions for each of the flights made during the tests on the two sets of blades are shown in chronological order in Tables I and II.

5.2 De-Icing Tests

The de-icing test data are also presented in Tables I and II. It should be noted that the on-times listed are for the individual sections of the heater mats and not for the entire de-icing cycle. On both sets of blades, there were slight variations in the extent of shedding between the two blades. On the chordwise shedding blades, blade A2-2 was used as the reference when plotting the results because of the cold spot on the leading edge of the other blade. On the spanwise shedding blades there was little difference between the two, and an average between them was used when plotting. These results are shown plotted in the form Ambient Temperature vs. Specific Energy for power densities of 20, 30 and 40 watts/sq. in. in Figures 7, 8 and 9 respectively for the chordwise shedding blades, and Figures 11, 12 and 13 respectively for the spanwise shedding blades. Various extents of shedding are noted by different symbols. Shedding was considered successful on all blades if ice was removed to 61 inches radius or better. The lines drawn which indicate the energy required for successful shedding have been replotted for comparison purposes in the form Time vs. Temperature in Figures 10 and 14. Finally, in Figure 15, the curves for both systems have been transposed to show the variation of Specific Energy with Power Density at three ambient temperatures.

On the spanwise shedding blades a few flights were made using an alternate blade shedding sequence. These tests showed that there was no change in the specific energy required for shedding and that there was no undue increase in vibration when asymmetric shedding is employed.

Both sets of blades contained some minor faults which affected the shedding results slightly. Small cold spots were evident between the heated areas of the mats and on the connecting busses. These cold spots produced small areas of ice anchorage on the blades and resulted in some runback ice.

Some examples of the shedding performance of the two systems are shown in Figures 16 to 21.

5.3 Extra Flights

Four special flights, beyond the scope of the comparison tests, were made to observe the effects of operating the de-icing systems with excessive on-times and of de-icing within the cloud.

On Flights C6-5 and S4-6, the rotor blades were iced and de-iced for a few cycles in the cloud at 30 watts/sq. in. and with excessive heat on-times; i.e. 10-second on-times were used where about $1\frac{1}{2}$ seconds would have been sufficient. The result of these tests was that considerable runback ice was formed on the blades (see Fig. 17c and 18, respectively).

On Flight S4-7, the rotor was de-iced for several cycles with the helicopter remaining in the cloud but with a marginal heat-on-time to the heater mats. De-icing was not completely successful and again there was runback (Fig. 19a), but to a lesser degree than with excessive on-times. On Flight S4-8, a single cycle of icing and de-icing was performed in the cloud using a marginal on-time. De-icing was complete and there was slight runback on the lower surface of the blade (Fig. 19b).

6.0 DISCUSSION

6.1 Test Procedure

As in previous tests (c.f. Ref. 1) the energy requirements for shedding were obtained by de-icing in clear air after suitable exposure to icing conditions in the simulated icing cloud, thus removing the variable of liquid water content from the shedding results. That this variable has less effect than expected may be seen from Flight S4-7. In this case the blades were de-iced in the cloud at an on-time marginal for complete de-icing in clear air. The result was, contrary to expectations, an incomplete shedding (Fig. 19a). It is also illustrated by Flights S4-8 and S4-9 where, with ostensibly identical conditions, de-icing was performed in and out of the cloud respectively. The only significant difference in the results of the sheddings was a slight increase in runback when de-icing was performed in the cloud (Fig. 19b and c). It appears that, at the low liquid water contents used, there is no significant difference in the energy required for shedding between in and out of cloud de-icing, particularly in comparison with the effect of variations in ice thickness.

In general the occurrence of snow precluded testing because (i) the pilot's task was made more difficult and (ii) snow was entrained in the ice accretion resulting in a higher rate of icing and modifying the form of the accretion by upsetting the normal heat balance. For this reason the flight series C1- and C3- were curtailed when snow started to fall. However, because of the delay caused by the heater element failure during Flights C5-1 and -2 and its subsequent repair, and in order to maintain the test schedule, it was necessary to continue Flight series C7- regardless of the onset of snow after the first flight of the day. It is regarded that the specific energy required for de-icing was little affected by the snow when de-icing out of the spray cloud, although an increase in runback was to be expected.

No testing was carried out at temperatures higher than about -6° C, since, above this temperature, when the ice accretion approached a thickness suitable for de-icing extensive self-shedding occurred, obviating the need to de-ice. For this reason the curves in Figures 7 to 14 intersect the temperature axis in the vicinity of -6° C rather than at 0° C. It is probable that the lines should have a slight curvature as they approach the temperature axis, but some confusion is caused in this region by the self-shedding effects and by the rather futile tendency on the part of the test personnel to shorten the accretion time in order to have some ice on the blades to shed, the reduced amount of ice thus accreted being less than otherwise considered necessary for good shedding. These light accretions, indicated in the figures by a flagged symbol, require slightly greater energy to shed. However, in view of the ready tendency to self-shed at these higher temperatures, the straight lines presented may be accepted without undue trepidation.

6.2 Comparison of the Systems

This series of tests demonstrated conclusively that the spanwise shedding method of rotor blade de-icing results in a considerable saving of energy over the chordwise shedding method. Figure 15 compares the specific energy required for shedding by the two systems and indicates that, although at -10° C there is nothing to choose between them, at -20° C a reduction in energy of 90 joules/sq. in. is obtained by spanwise shedding at 30 watts/sq. in., a reduction of 31 percent over the chordwise method. This improvement increases with power density and with decreasing temperature. Such a saving of energy is without doubt very worth while.

The spanwise shedding system also permits a further saving of energy by the adoption of alternate blade de-icing, whereby energization of the heated areas proceeds in alternate manner from blade to blade (i.e. 1A, 1B, 2A, 2B, 3A, etc.) instead of in a symmetrical sequence (i.e. 1A and 1B, 2A and 2B, etc.). This is possible because of the low level of unbalance and vibration in the spanwise sequence system when asymmetric de-icing is used compared with that in the chordwise method. Certain aspects of asymmetric de-icing are discussed in Reference 1.

The performance of chordwise shedding may be made to approach that of spanwise shedding if the heater strips are made sufficiently wide; in particular, the leading edge strip must be wide enough to accommodate completely the main ice formation (i.e. all but the secondary feathery or frosty formation). Such a wide coverage (say 2 in.) would demand very high installed generating capacity, and therefore is impractical. An attempt in this direction has been made (see Ref. 4); strips 1½ in. wide were utilized, the de-icing mats having essentially the same construction as those used in this present series of tests. The specific energy required was lower than for the present 1-in. strips, but was still greater than that required for the spanwise shedding system. Also in this case, since only 3 strips were needed to cover the same area as that covered by the 5 heated areas used in the spanwise shedding system, total power requirements were increased by 67 percent, energy requirements even more.

A very slight reduction in runback was noted for the spanwise shedding method as compared with chordwise shedding. This runback was generally light and confined mainly to the undersurface of the inner half of the blades; its presence was therefore of rather minor importance. Examples of typical runback when de-icing in clear air are shown in Figures 16, 17a and b (for chordwise shedding) and Figure 21 (for spanwise shedding).

Flights S4-8 and S4-9 were designed not only to investigate shedding time variations between "in cloud" and clear air shedding, as discussed in Section 6.1, but also to determine whether droplet impingement during de-icing had any marked influence on the degree of runback. The clear air shedding of Flight S4-9 exhibited no runback (Fig. 19c), while de-icing in the cloud (Flight S4-8) produced some in slight degree; this is barely visible in Figure 19b. When a series of 4 icing and de-icing cycles in the cloud was made (Flight S4-7) runback was more extensive (Fig. 19a), yet consisted still of light isolated streaks of runback ice of negligible aerodynamic importance. These streaks are made clearly visible in the photographs by a light frost formation on them caused by a supersaturated condition within the icing cloud resulting from high ambient relative humidity.

6.3 Excessive On-Time

Runback of a more severe nature than that demonstrated on Flight S4-7 resulted from using heating times appreciably in excess of that just necessary to effect shedding. This heavy runback is illustrated in Figures 17c and 18 for chordwise and spanwise shedding respectively. In both cases an on-time of 10 seconds at 30 watts/sq. in. was used; times of 1 second and 2 seconds respectively would have sufficed. No adverse aerodynamic effects were apparent during these short encounters requiring two and three de-icing cycles respectively, but for lengthy icing encounters such runback deposits could accumulate to considerable proportions. Clearly then, a fixed on-time system (implying excessive on-times at higher temperatures) is undesirable quite apart from the wastage of energy involved.

6.4 De-Icing Heater Mats

Thus far it would appear that there is little to commend a chordwise shedding system. It has, however, one important practical advantage, and that is its greater simplicity of manufacture and of installation on the rotor blade. Reference to Figures 2 and 3 demonstrates this quite clearly. In particular, it will be noted in the spanwise shedding system that supply leads must run to varying extents along the blade; indeed the common lead must run the entire length of the blade. It is probable that provision could be made in the design of a blade to accommodate such leads, but in the experimental system here tested, flat braided leads embedded in synthetic resin were bonded to the upper and lower surfaces to the aerodynamic detriment of the blades; the view of the upper surface of the blade in Figure 18 demonstrates this.

Nevertheless, in spite of the greater difficulties experienced in constructing the mats for spanwise shedding, no failures or burn-outs were experienced as was the case with the chordwise shedding mats (see Appendix A). The precise cause of failure was not apparent.

7.0 CONCLUSIONS

A marked saving in both electrical power and energy is achieved by a rotor blade de-icing system using the spanwise shedding method as compared with the chordwise shedding method.

By utilizing the asymmetric blade de-icing capabilities of the spanwise shedding system even greater power savings can be realized.

Spanwise shedding results in slightly cleaner de-icing (i.e. less runback) than chordwise shedding.

The chordwise shedding system has the advantage of greater simplicity of construction and thus of lower initial cost.

Owing to their respective merits, the spanwise shedding method lends itself to applications where electrical generating capacity is at a premium and in particular to the small helicopter, while the chordwise shedding system may be used in applications where first cost is of major importance.

8.0 ACKNOWLEDGEMENTS

Greatful acknowledgement is made to the U.S. Navy, Bureau of Aeronautics, for making available the two sets of rotor blades used in these tests, and also to the Goodyear Tire and Rubber Co. who provided, at their own expense, the woven wire heater elements used in the de-icing mats, which were constructed by the Bell Helicopter Corporation.

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TABLE I

CHORDWISE SHEDDING DATA

Flight No.	Corrected Temp. (°C)	L.W.C. (gm./m^3)	Time in Icing (min.)	Max. Thickness (in.)	Power Density (watts/in^2)	On Time (sec.)	Specific Energy (joules/in^2)	Extent of Shedding Blade A2-1 (in.)	 Blade A2-2 (in.)	Remarks
C1-1	-12.[illegible]	0.3	3.2	3/16	30	7	210	57	57	Snowing. Runback on lower surface at 84". Runback on upper surface at 80".
C2-1	-12.[illegible]	0.08*	7.3	3/16	30	9	270	160	116	Cold spot on Zone 4 at 140" on blade A2-2 causing slight runback.
C2-2	-22.2	0.1*	5.5	3/16	30	11	330	150	70	Severe vibration during shedding.
C2-3	-21.9	0.1*	6.25	11/64	40	7	280	130	74	Runback on lower surface at 86" and 150".
C3-1	-12.4	0.1*	8.5	-	-	-	-	-	-	Extensive self-shedding. Vibration.
C3-2	-12.3	0.15*	6.25	3/16	40	3	120	6[illegible]	56	
C3-3	-12.3	0.15	5	-	30	5	150	88	57	Slight runback on lower surface 60" - 100". Slight streak on upper surface at 105".
C3-4	-12.0	0.2	4.5	-	30	4½	135	85	57	Runback as Flight C3-3.
C3-5	-11.4	0.25	4.75	-	30	3	90	99	57	
C3-6	-11.4	0.25	3.75	-	30	2	60	137	112	
C3-7	-11.1	0.25	3.25	-	30	2½	75	110	74	Slight runback as Flight C3-3.
C3-8	- 9.9	0.35*	3.5	11/64	30	2½	75	70	57	Slight runback on lower surface 60" to 90".
C3-9	- 9.6	0.2	4.2	-	30	2	60	108	57	
C3-10	- 9.8	0.2	4.1	3/16	40	1½	60	57	57	
C3-11	- 9.9	0.15	5	1/8 +	40	1	40	124	100	
C3-12	- 9.6	0.25	3.5	1/4	30	1½	45	116	81	Light snow falling.
C4-1	-16.3	0.225*	4	3/16	30	6½	195	120	57	Slight runback.
C4-2	-15.8	0.1*	6.25	1/8 +	30	5½	165	120	120	Runback on lower surface 60" to 125".
C4-3	-15.8	0.2*	3.5	1/8	40	4	160	115	118	
C4-4	-15.8	0.15*	6	5/32 +	40	4½	180	119	57	Slight runback on lower surface of A2-2 from 60" to 90".
C5-1	-16.9	0.3*	2.4	9/64	30	7	-	-	-	Shedding unsuccessful due to heater element failure
C5-2	-15.6	0.2*	2.4	1/8	30	6	-	-	-	
C6-1	- 7.0	0.25	3.4	-	30	½	15	130	130	Blades had self-shedding to ≈ 130". No shedding of remaining ice.
	- 6.8	-	-	-	30	1	30	57	57	Second attempt at previous operation.
C6-2	- 6.6	0.15	2.2	3/32	20	1	20	134	103?	Blade A2-2 had self-shed to 103" and shed no further electrically.
C6-3	- 6.7	0.25	2.3	3/32	20	1½	30	86	57	
C6-4	- 6.7	0.2	2.3	1/16 +	40	½	20	81	57	
C6-5	- 6.6	0.25	6	-	30	10	300	57	57	Deliberate excessive on-time. 2 cycles at 2½ min. intervals. Considerable runback.
C6-6	- 6.3	0.2*	3.5	3/32	30	½	15	130	127	
C7-1	-10.3	0.3	2.5	trace						Insufficient ice accretion for shedding.
C7-2	-10.8	0.3	3	11/64	20	3	60	125	69?	Light snow falling. Slight runback. A2-2 may have self-shed to 69".
C7-3	-10.8	0.25	3	5/32	20	3	60	164	73	Snowing. Severe vibration after de-icing.
C7-4	-10.7	0.2	2.7	-	20	1	20	No shedding	171?	Snowing. Blade A2-2 may have self-shed to 171".
	-10.7	-	-	-	20	3½	70	119 & 88 to 63	60½	Second attempt.
C7-5	-10.4	0.25	3.1	-	20	4	80	122	57	Snowing. Slight runback on lower surface 145" - 50".
C7-6	- 9.2	0.25	2.7	11/64	30	1	30	154	81	Snowing.
C7-7	- 8.9	0.25	3.5	5/64	20	2½	50	127	57	Snowing.
C7-8	- 9.[illegible]	0.25	3.5	1/8	40	½	20	129	114	Snowing.
C7-9	- 8.7	0.25	3.5	-	40	1	40	108	57	Snowing.
C7-10	- [illegible]	0.25	3.75	-	20	1½	30	133	100	
C7-11	- 8.4	0.2	3.5	-	20	2	40	117	76	Light snow.
C7-12	- 8.4	0.25	3.5	11/64	30	1	30	121	86	
C7-13	- 7.5	0.25	3.3	-	40	½	20	150	57	Snowing.
C8-1	-22.1	0.1*	5.1	3/32	40	-	-	-	-	Very gusty. Heater element failure in blade A2-2.

* L.W.C. determined by ice accretion measurements after flight.

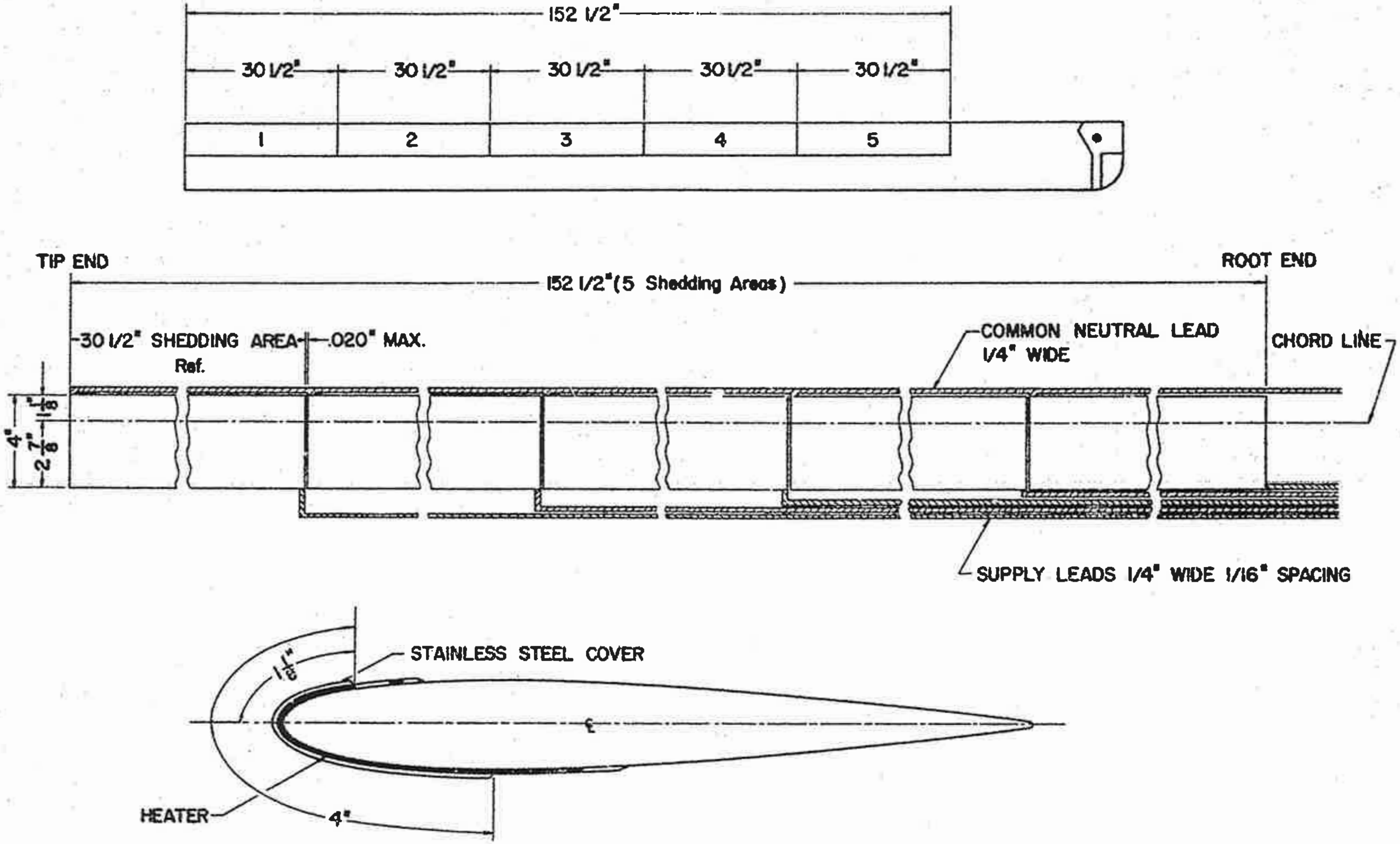
TABLE II

SPANWISE SHEDDING DATA

Flight No.	Temp. (°C)	L.W.C. (gm./m^3)	Time In Icing (min.)	Ice Thickness (in.)	Power Density (watts/in.^{2})	On Time (sec.)	Specific Energy (joules/in.^{2})	Extent of Shedding Blade A2-413 (in.)	Extent of Shedding Blade A2-415 (in.)	Remarks
S1-1	-12.0	0.13*	6.2	1/8 at 130"	-	-	-	-	-	Blade A2-413 had self-shed to 145", A2-415 to 93". Remainder melted in sun during inspection, precluding de-icing.
S1-2	-10.3	0.1	4.3	-	-	-	-	-	-	Unserviceability in de-icing selector box.
S1-3	- 8.6	0.1	4	3/32 at 115"	30	1	30	115	115	Some self-shedding prior to de-icing.
S1-4	- 8.9	0.1	3.2	1/16 at 99"	30	1½	45	102	99	Some self-shedding prior to de-icing.
S1-5	- 8.3	0.1	3.2	5/64 at 69"	30	2	60	40	69	Some self-shedding prior to de-icing.
S2-1	-16.9	0.2	3.5	11/64 at 61"	30	6	180	61	61	Slight runback.
S2-2	-15.6	0.2	3.3	9/64 at 88"	30	4	120	87	88	Small cold spots on lower surface at busses.
S2-3	-14.6	0.2	3.5	-	30	4	120	61	61	Some small cold spots.
S2-4	-12.8	0.15	4	7/64 at 81"	30	3	90	71	81	
S2-5	-12.3	0.2	3.75	3/32 at 70"	30	3	90	70	61	
S2-6	-11.9	0.2	4.5	9/64 at 84"	30	2½	75	61	64	
S2-7	-11.0	0.25	4	1/8 at 70"	30	2½	75	70	61	Alternate blade de-icing.
S2-8	-10.0	0.15	3.75	1/16 at 65"	30	2	60	65	61	Alternate blade de-icing.
S2-9	- 9.5	0.15	3.75	1/8 at 88"	30	1½	45	73	88	Alternate blade de-icing.
S2-10	- 9.7	0.25	3.3	1/8 at 85"	40	1	40	73	85	Alternate blade de-icing.
S2-11	- 9.0	0.25	3.5	1/8 at 77"	40	1	40	61	77	Alternate blade de-icing.
S3-1	- 8.7	-	2.5	11/64 at 130"	20	2	40	94	-	Wind calm. Some self-shedding prior to de-icing.
S4-1	- 9.2	0.3	2.8	3/32 at 62"	40	1½	60	62	62	
S4-2	- 9.4	0.25	2.1	9/64 at 160"	40	½	20	172	190	
	- 9.2		-		40	1½	60	68	61	2nd cycle to clear ice.
S4-3	- 9.2	0.3	2.75	5/64 at 61"	20	3	60	62	61	
S4-4	- 9.2	0.25	3	1/8 at 90"	20	2	40	86	98	Some self-shedding prior to de-icing.
S4-5	- 9.4	0.25	3.2	3/16 at 164"	20	1	20	155	164	
S4-6	- 8.7	0.1	10	-	30	10	300	-	-	3 cycles at excessive on-time. Considerable runback.
S4-7	- 8.4	0.15	9.2	-	30	1½	45	109	108	Extended run. 4 cycles. Marginal on-time. Runback.
S4-8	- 8.0	0.3	3.1	-	30	1½	45	65	61	De-icing in cloud. Runback on lower surface.
S4-9	- 7.8	0.2	3.5	-	30	1½	45	61	61	De-icing out of cloud.
S4-10	- 7.5	0.25	2.5	5/64 at 60"	40	1	40	65	80	
S4-11	- 7.1	0.25	3.75	7/64 at 91"	20	2	40	91	85	
S4-12	- 7.0	0.15	4	3/32 at 68"	30	1	30	63	68	Some self-shedding before de-icing.
S5-1	-18.2	0.3	2.5	3/32 at 62"	40	5	200	61	62	
S5-2	-18.1	0.3	2.5	-	40	4½	180	61	61	Small patch of ice left at 153" on A2-413.
S5-3	-18.1	0.3	2.7	5/32 at 82"	40	3	120	80	82	
S5-4	-18.4	0.25	2.3	1/8 at 130"	30	5½	165	153	120	Alternate blades.
	-16.2	-	-	-	30	6½	195	61	61	Second attempt. Patches of ice left 65" to 100". Slight runback 60" - 120".
S5-5	-18.1	0.2	3	1/8 at 125"	20	9	180	127	125	Ice broken at 90" and only loosely anchored to blades 90" to 125".
S5-6	-17.4	0.25	3	3/32 at 63"	20	10	200	61	63	Slight patches of ice remain at cold spots between heated areas.
S5-7	-16.6	0.3	3	3/32 at 62"	40	4	160	62	61	
S5-8	-16.3	0.15	2.7	5/64 at 92"	30	5	150	92	91	Slight runback.
S5-9	-16.0	0.3	3.2	11/64 at 110"	30	3	90	112	120	
S5-10	-16.0	0.3	3.3	9/64 at 61"	30	4½	135	61	6[illegible]	
S5-11	-15.0	0.3	3.3	5/32 at 65"	20	8	160	62	65	
S5-12	-14.7	0.3	3.5	9/64 at 62"	20	5	100	50	62	
S5-13	-14.1	0.3	3.5	1/8 at 62"	40	3	120	62	61	
S5-14	-13.9	0.25	2.7	1/8 at 62"	40	2½	100	62	61	
S5-15	-13.7	0.3	2.1	1/8 at 76"	40	2	80	68½	76	
S5-16	-13.3	0.3	2.3	7/64 at 62"	20	7	140	62	61½	
S5-17	-12.7	0.3	2.5	9/64 at 120"	20	3	60	134½	123½	
S5-18	-12.3	0.3	2.7	5/32 at 64"	40	2	80	64	61	
S5-19	-11.9	0.3	2.5	5/64 at 62"	20	5	100	62	61	
S5-20	-11.9	0.3	2.5	9/64 at 115"	30	1	30	178	211	
	-11.8		-	-	30	1½	45	153	149	Second attempt.

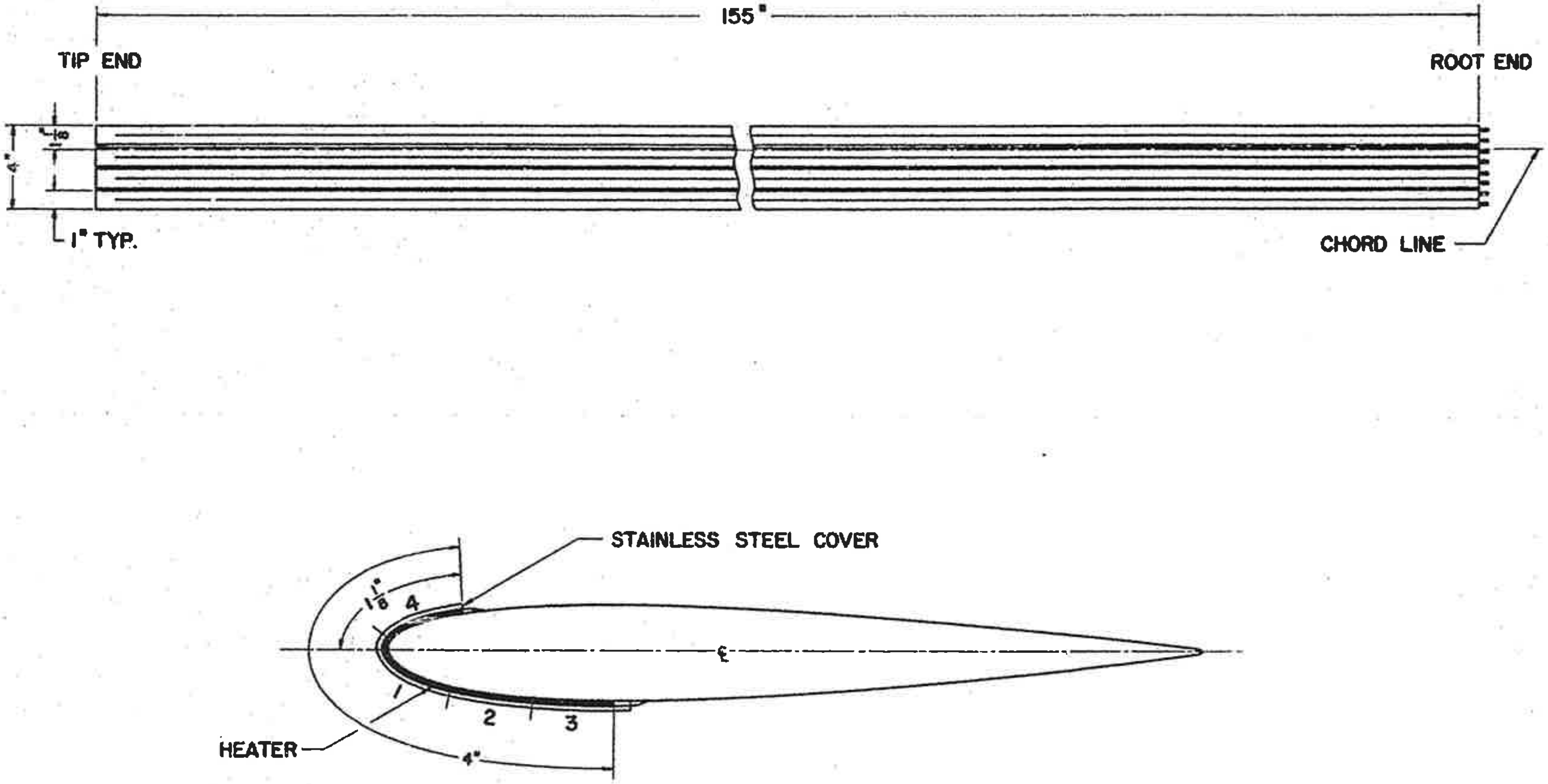
* L.W.C. determined by ice accretion measurements after flight.

THE TEST HELICOPTER



CHORDWISE ELEMENTS FOR SPANWISE SHEDDING.

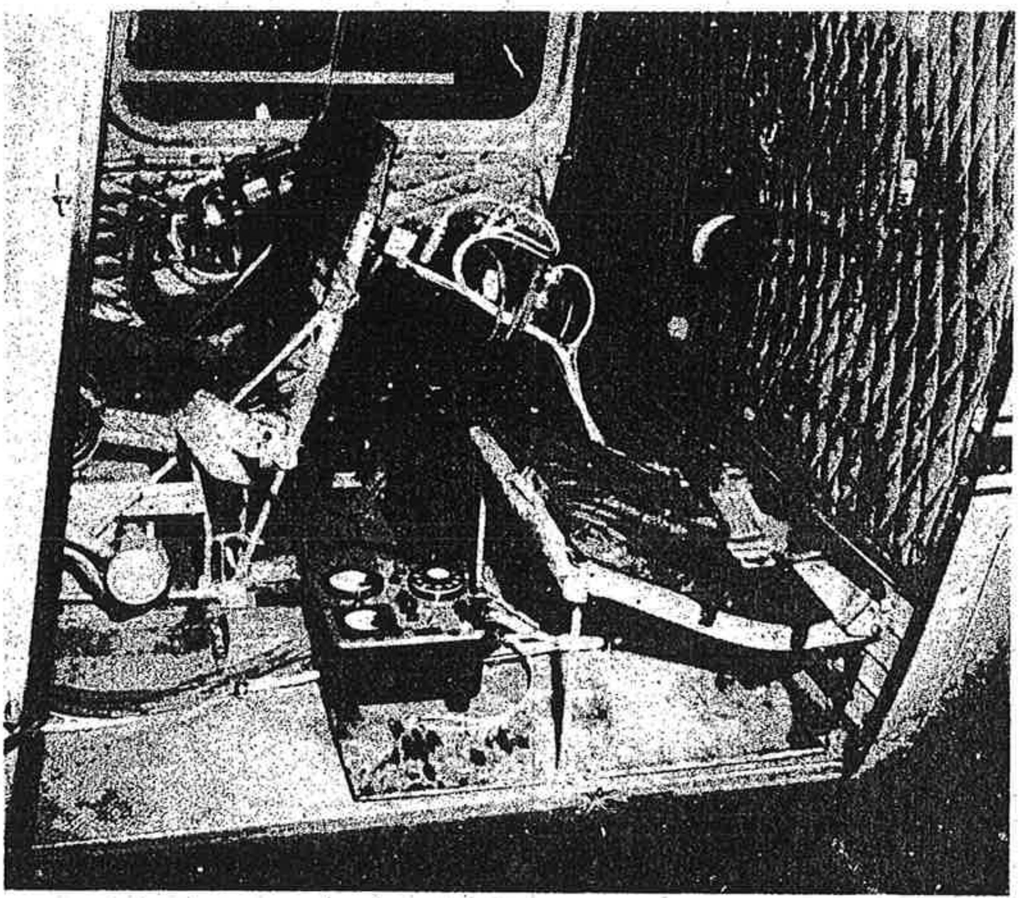
FIG. 2
LR-270



SPANWISE ELEMENTS FOR CHORDWISE SHEDDING.

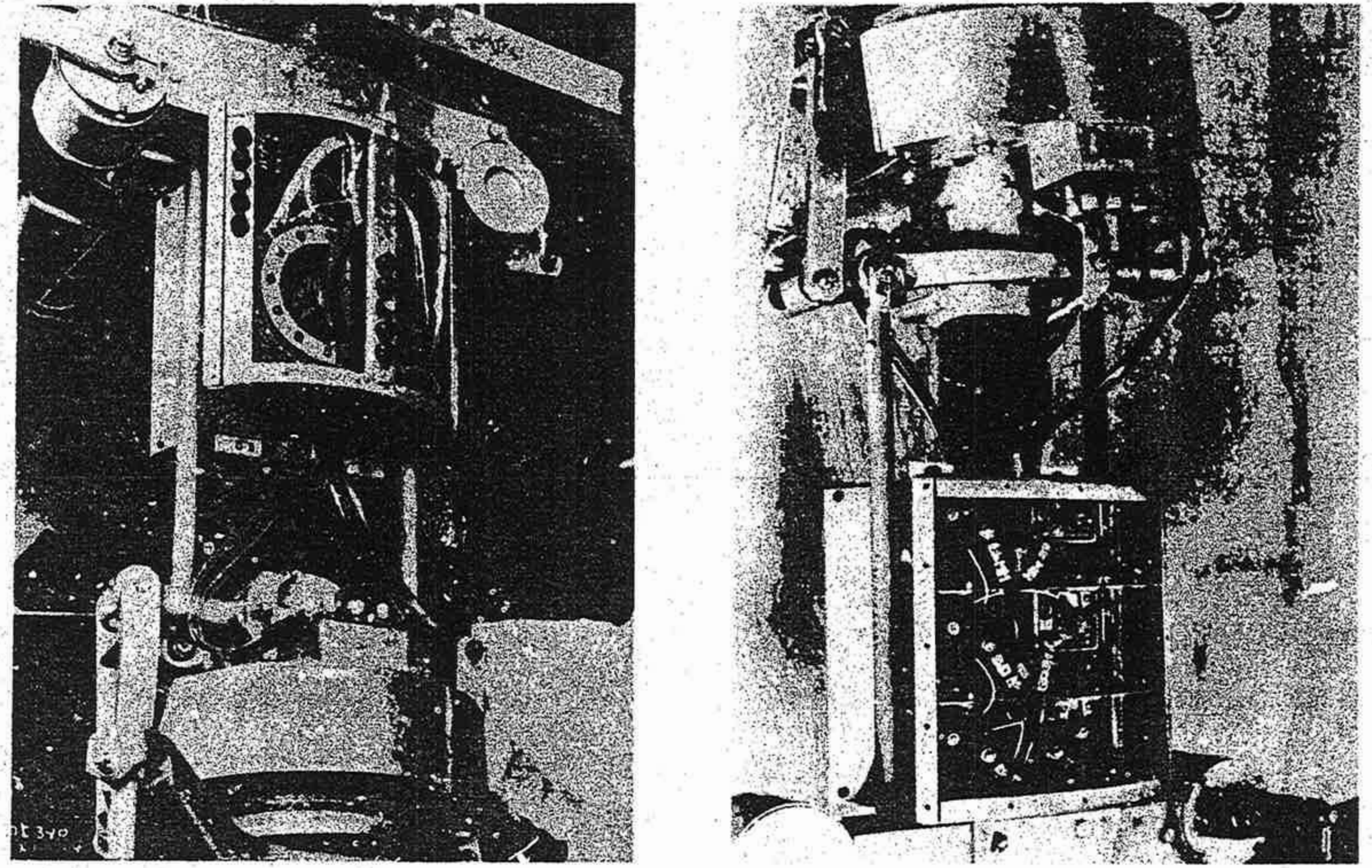
FIG. 3
LR-270

FIG. 4
LR-270



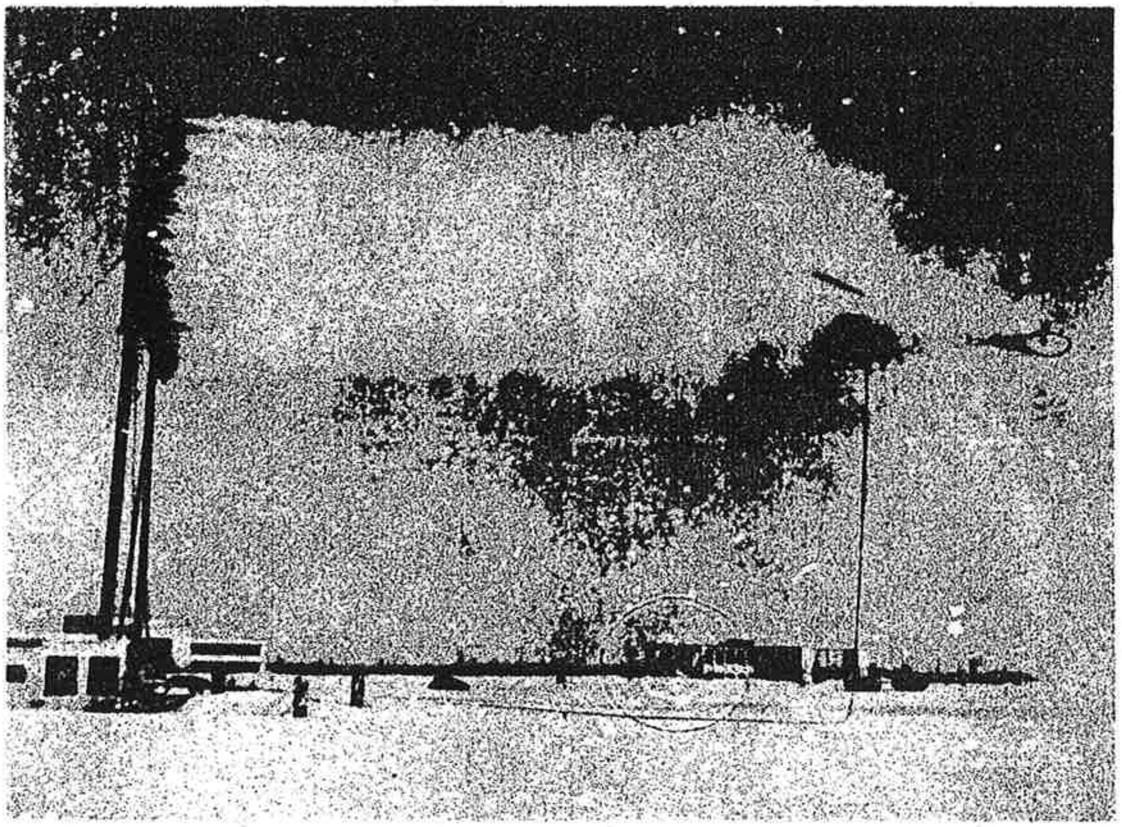
DE-ICING CONTROL GEAR AND INSTRUMENTATION
INSTALLED IN AIRCRAFT CABIN

FIG. 5
LR-270



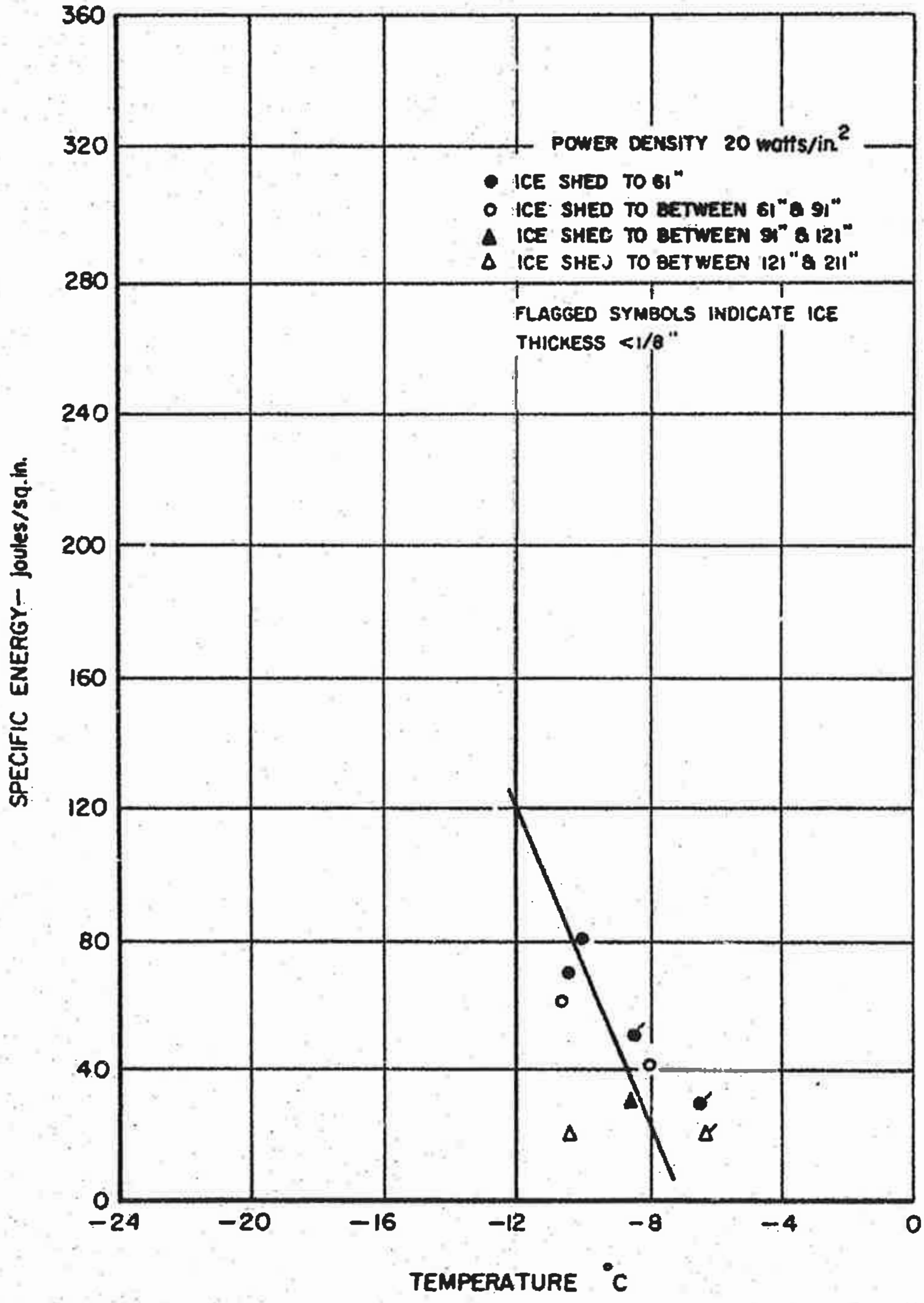
SLIP RING AND SELECTOR SWITCH ASSEMBLIES

FIG. 6
LR-270



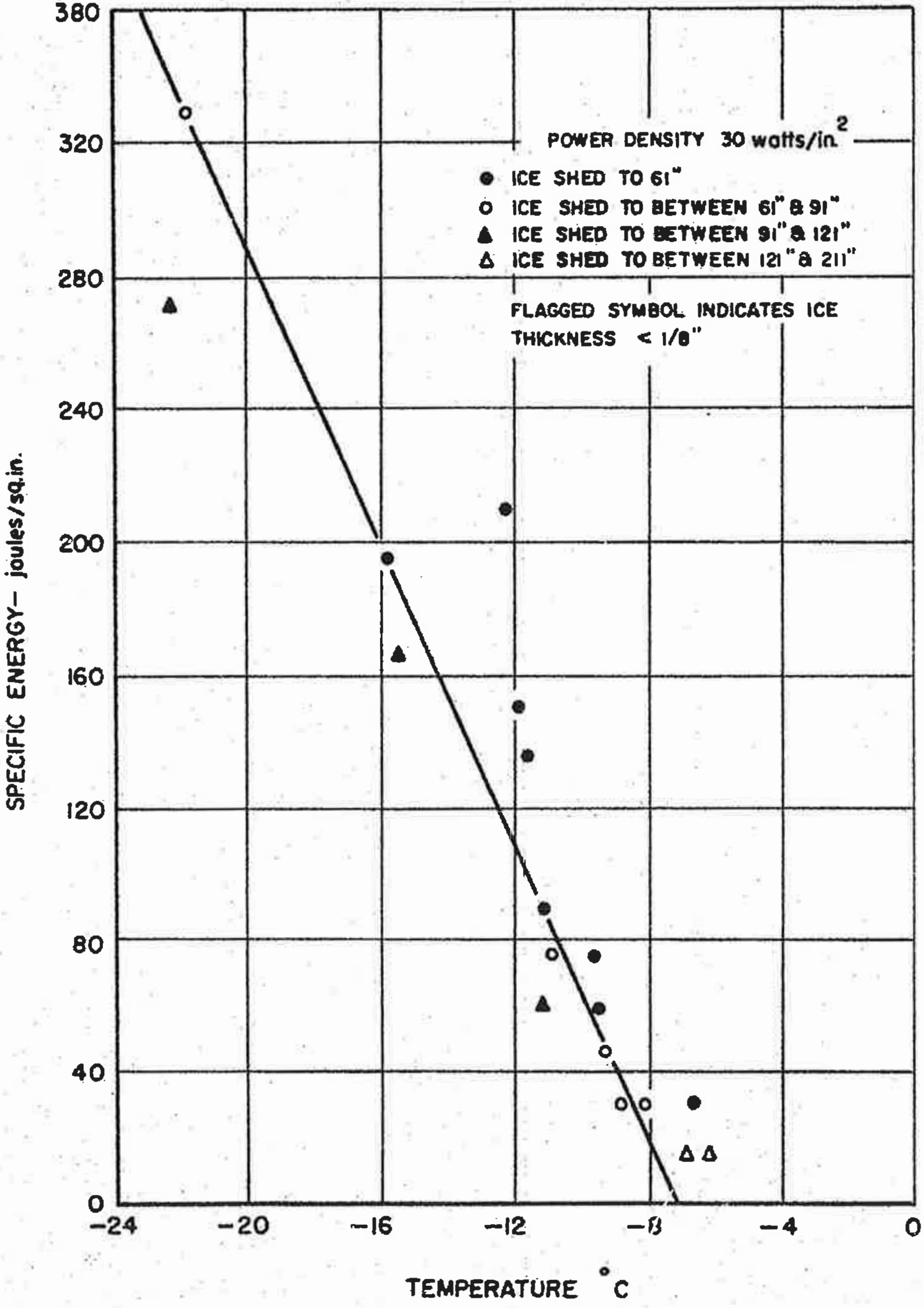
SPRAY RIG WITH HELICOPTER IN FLIGHT

FIG. 7
LR-270



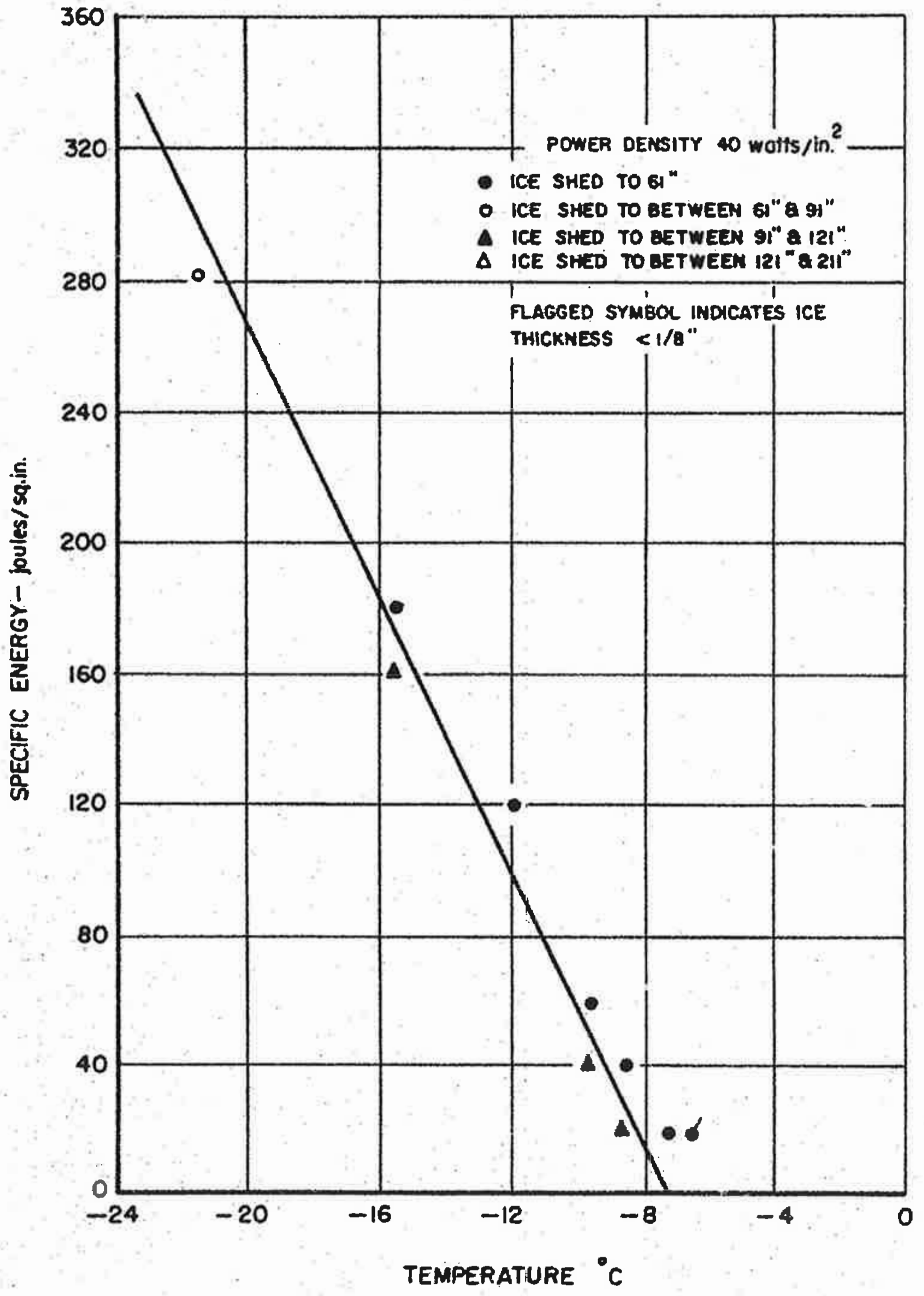
TEST RESULTS AT A POWER DENSITY OF 20 WATTS / SQ. IN. CHORDWISE SHEDDING.

FIG. 8
LR-270

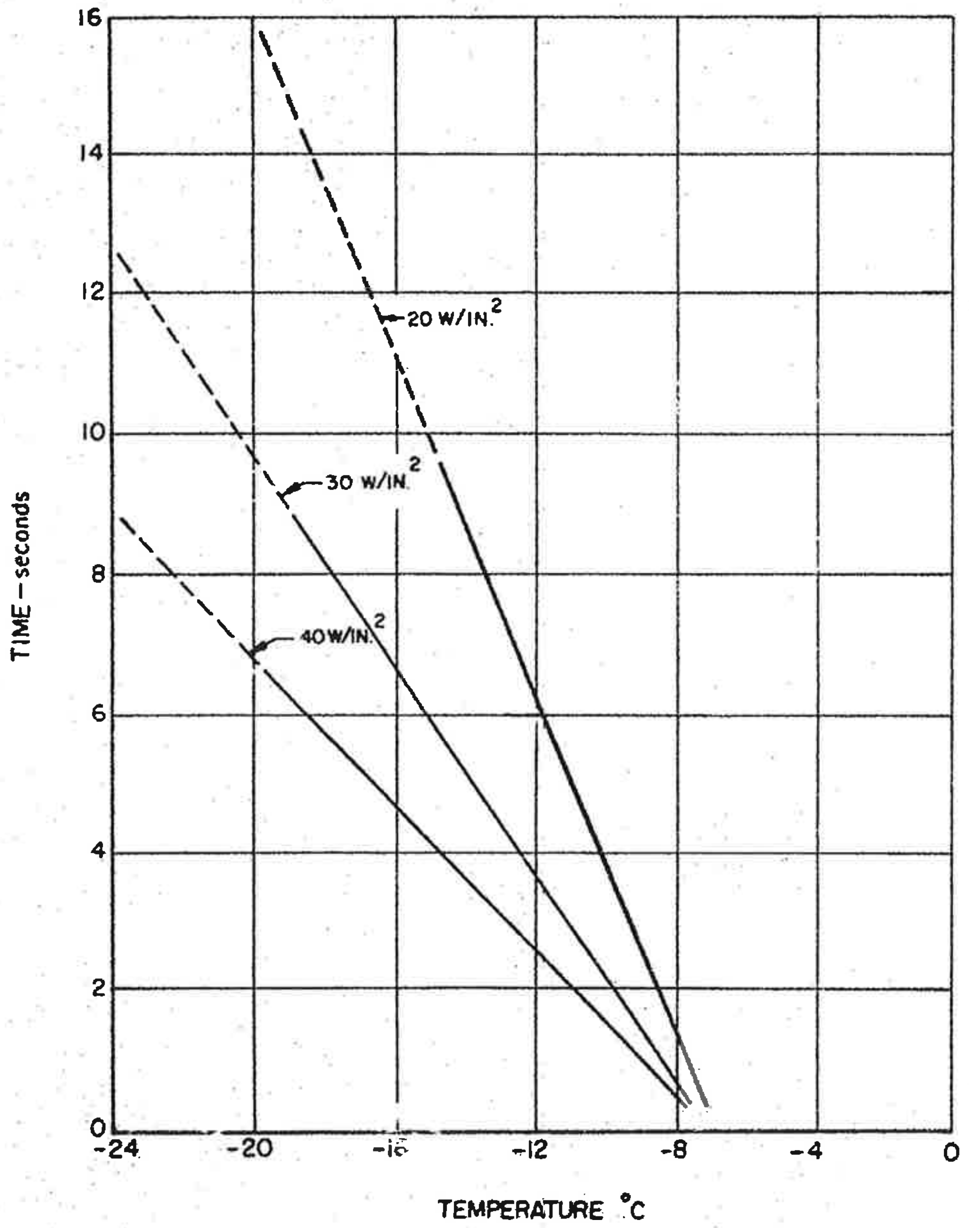


TEST RESULTS AT A POWER DENSITY OF 30 WATTS/SQ.IN.
CHORDWISE SHEDDING.

FIG. 9
LR-270



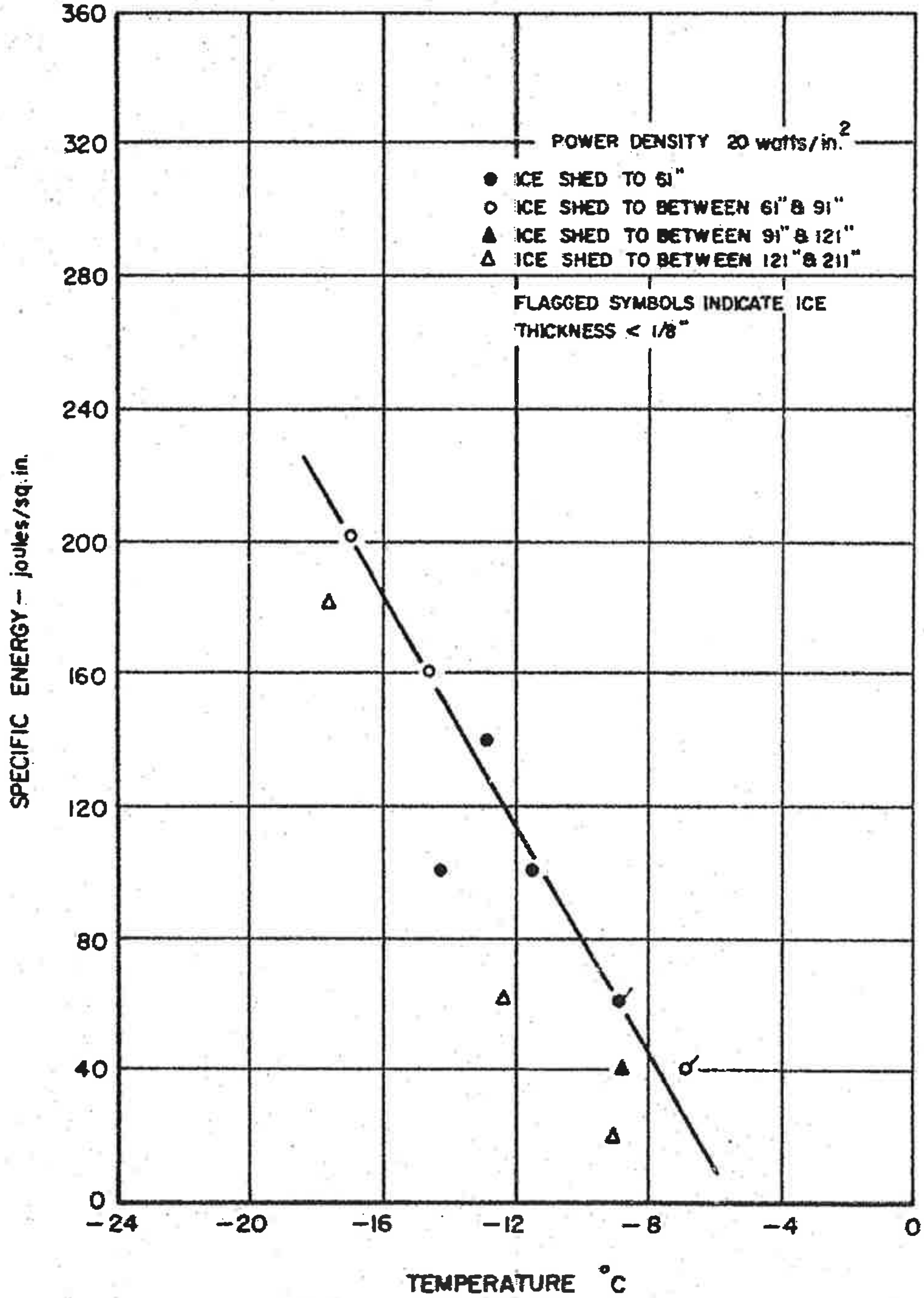
TEST RESULTS AT A POWER DENSITY OF 40 WATTS / SQ. IN.
CHORDWISE SHEDDING.



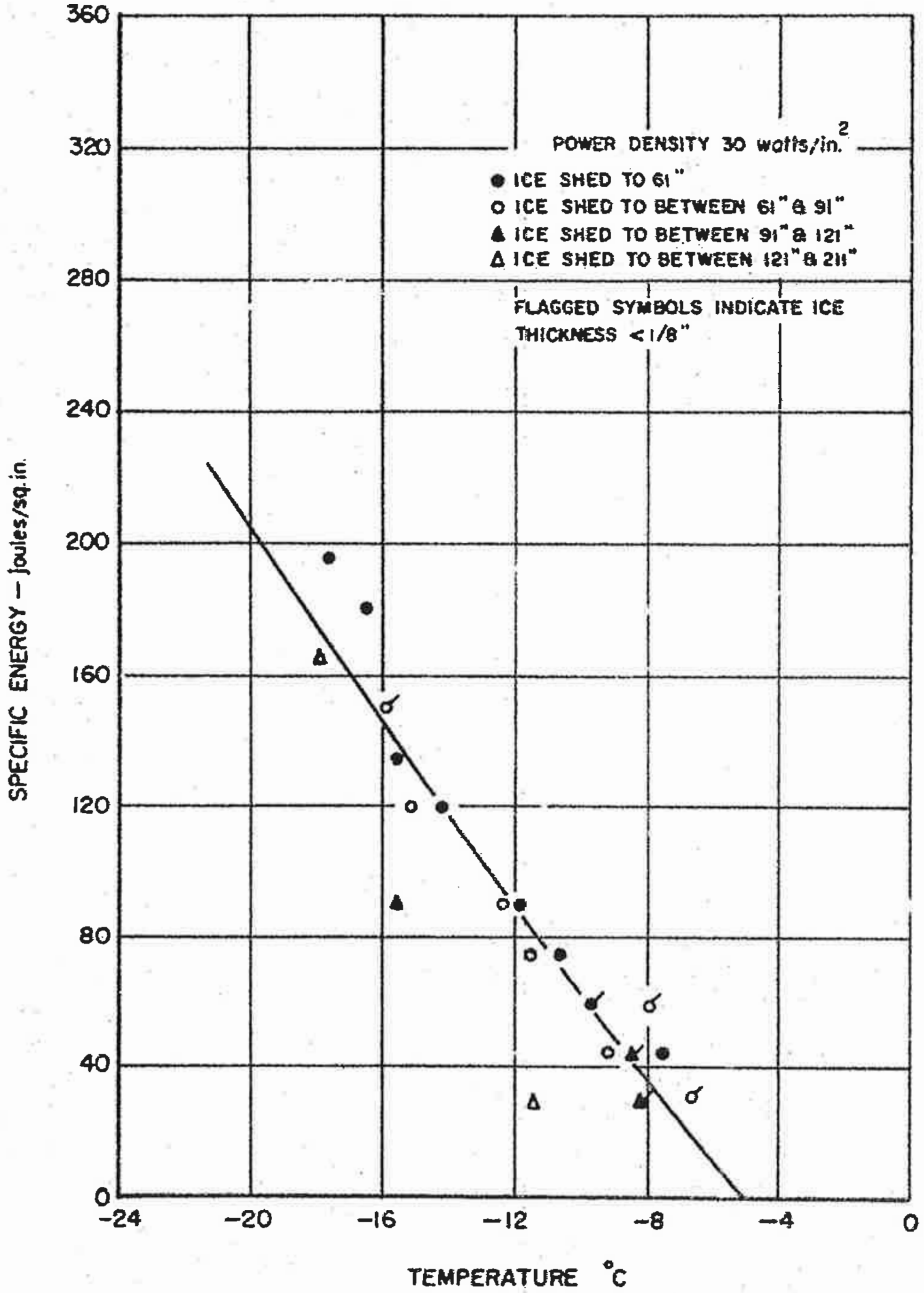
POWER-ON-TIME REQUIRED FOR SHEDDING TO 5-FOOT RADIUS CHORDWISE SHEDDING.

(Data from Fig. 7, 8 and 9)

FIG. 11
LR-270

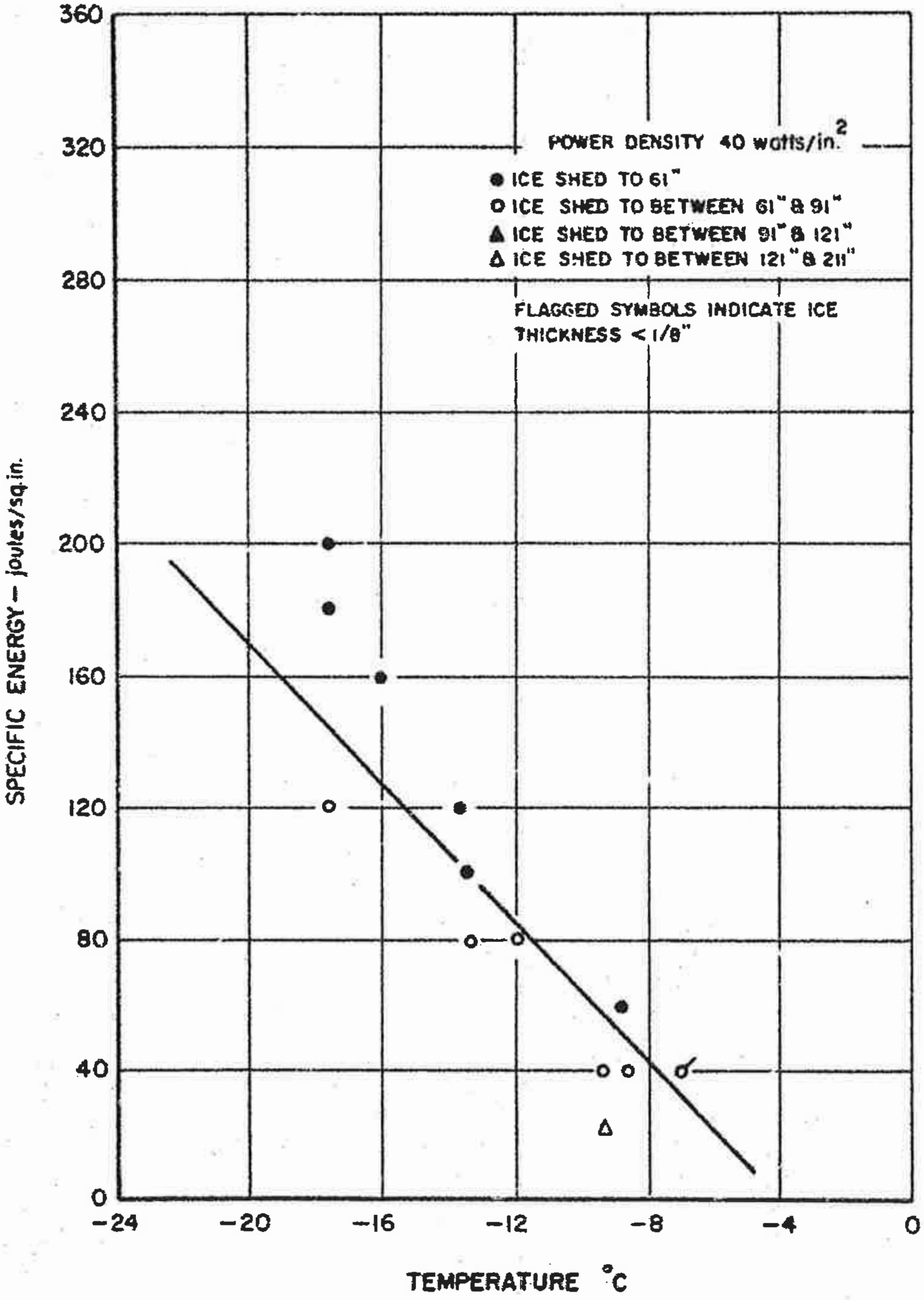


TEST RESULTS AT A POWER DENSITY OF 20 WATTS / SQ. IN.
SPANWISE SHEDDING.



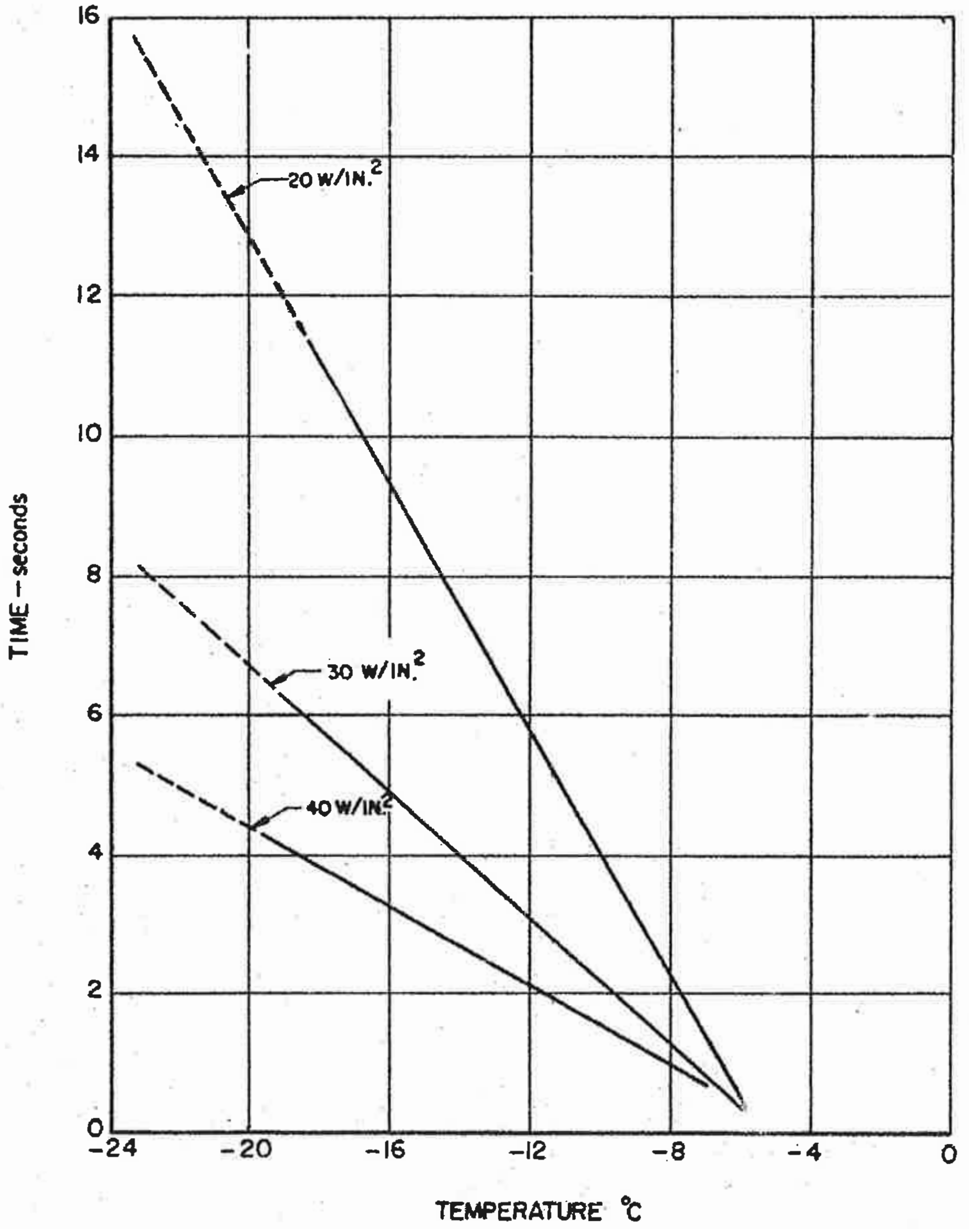
TEST RESULTS AT A POWER DENSITY OF 30 WATTS / SQ. IN.
SPANWISE SHEDDING.

FIG. 13
LR-270



TEST RESULTS AT A POWER DENSITY OF 40 WATTS /SQ. IN.
SPANWISE SHEDDING.

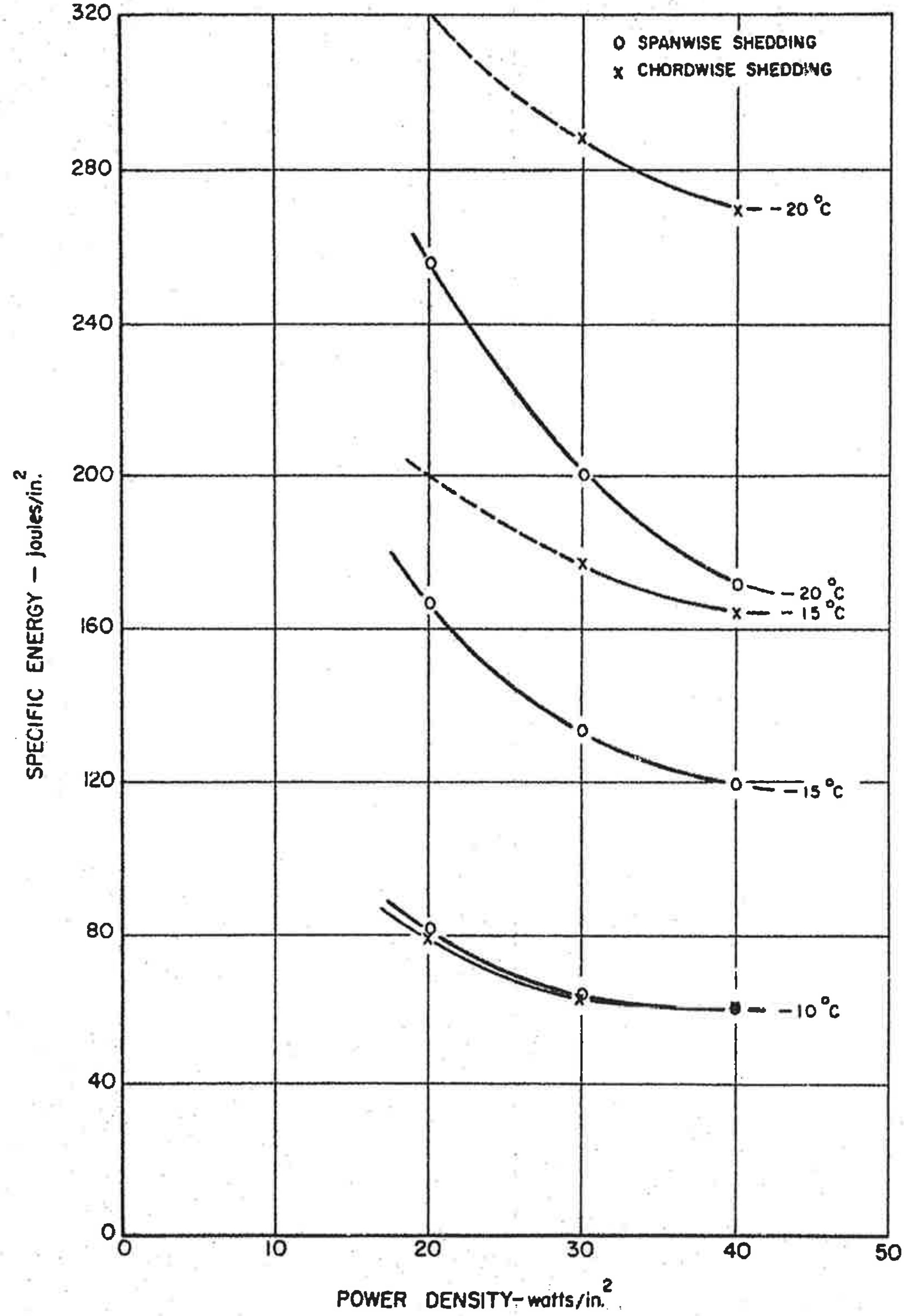
FIG. 14
LR-270



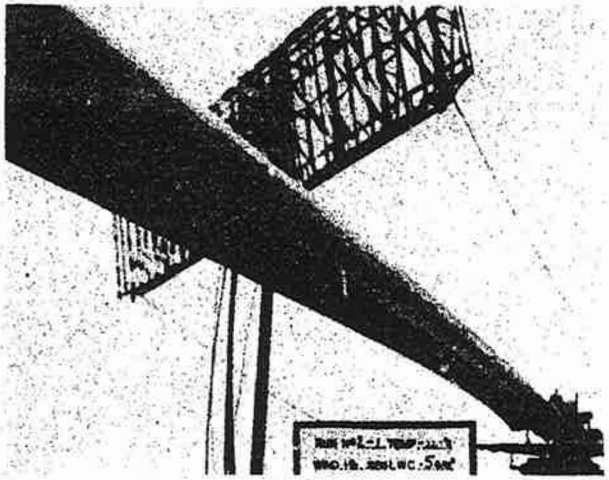
POWER – ON – TIME REQUIRED FOR SHEDDING TO 5-FOOT RADIUS SPANWISE SHEDDING.

(Data from Fig. 11, 12 and 13)

FIG. 15
LR-270



SPECIFIC ENERGY REQUIRED FOR SHEDDING TO 5-FOOT RADIUS SPANWISE AND CHORDWISE SHEDDING.



(a) ICE ACCRETION BEFORE DE-ICING

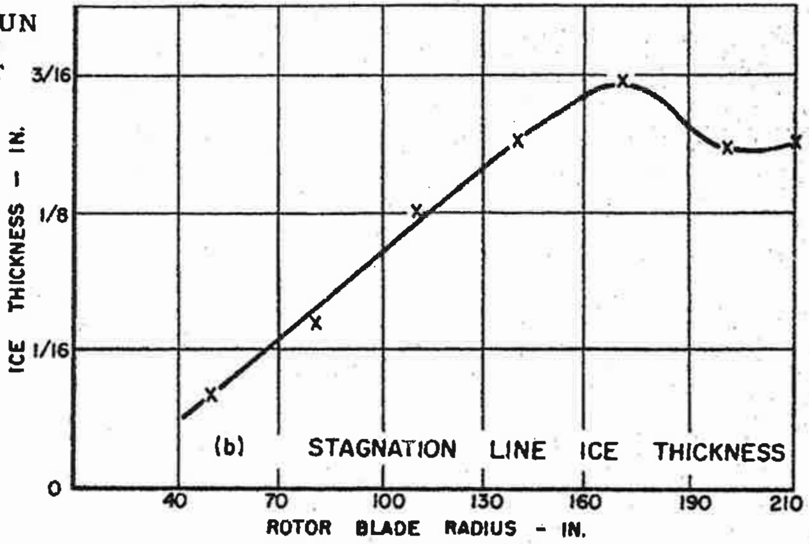
(a) AND (b) ICING RUN

CORRECTED AMBIENT TEMP. -23.3°C

CORRECTED L.W.C. 0.1 GM./M.^{3}

DROPLET SIZE 30 MICRONS

TIME IN ICING 7.3 MIN.



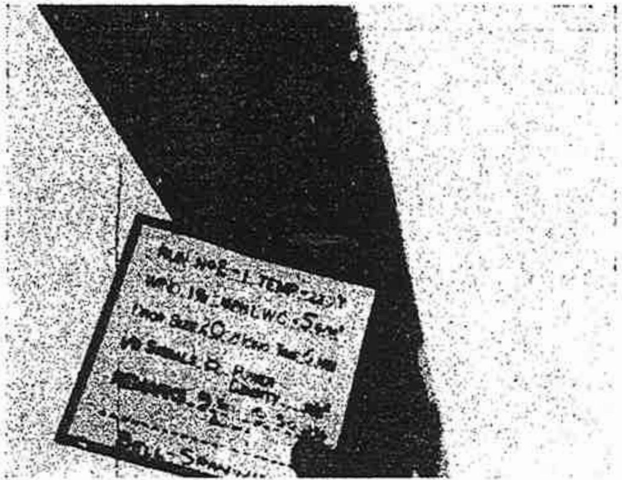
(b) STAGNATION LINE ICE THICKNESS

(c) AND (d) DE-ICING RUN

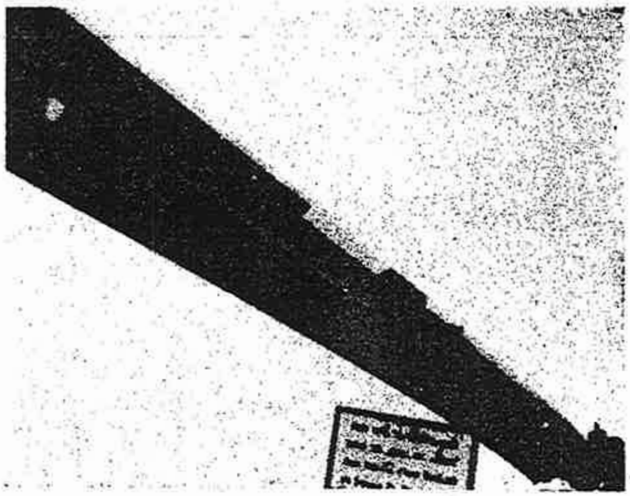
CORRECTED AMBIENT TEMP. -22.9°C

POWER DENSITY 30 WATTS/IN.^{2}

ON-TIME 9 SEC. INCOMPLETE SHEDDING



(c) RUNBACK FROM COLD SPOT

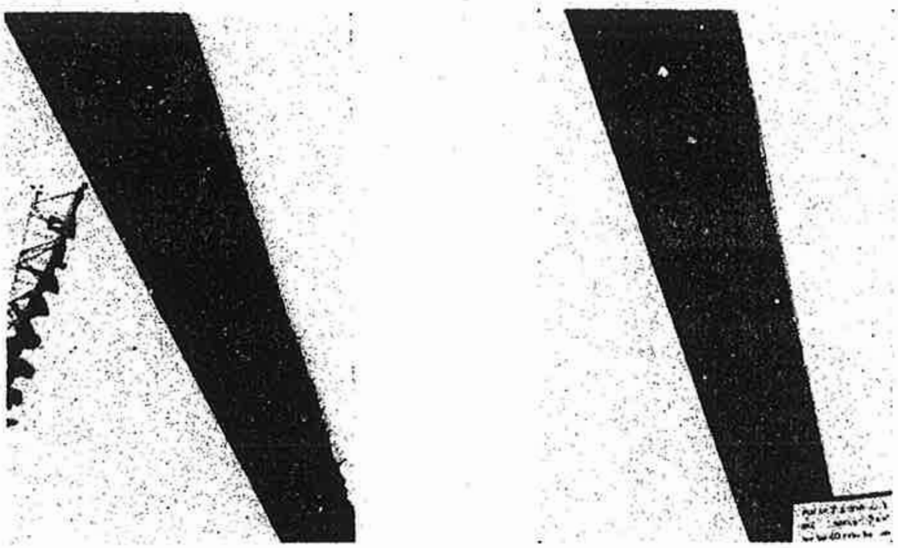


(d) RESIDUAL ICE AFTER DE-ICING

CHORDWISE SHEDDING AT LOW TEMPERATURE - FLIGHT C2-1

FIG. 16
LR-270

FIG. 17
LR-270

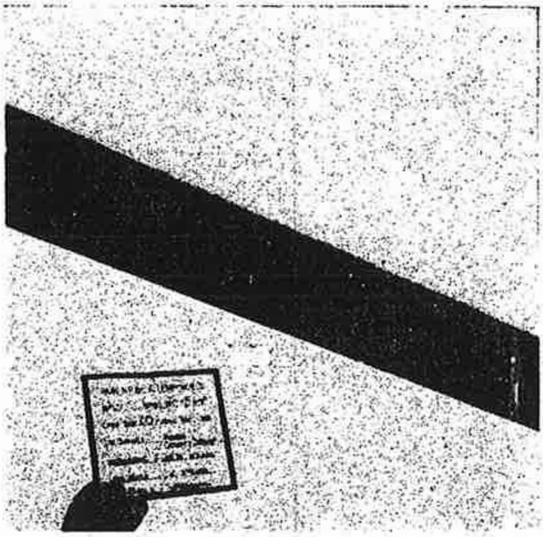


(a) SUCCESSFUL SHEDDING
FLIGHT C4-4

CORRECTED AMBIENT TEMP. -15.8°C
POWER DENSITY 40 WATTS/IN.^{2}
ON-TIME 4.5 SEC.

(b) COLD SPOTS ON BLADE
FLIGHT C7-5

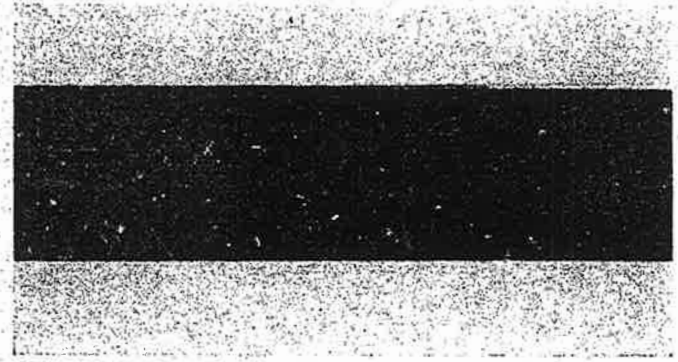
CORRECTED AMBIENT TEMP. -10.4°C
POWER DENSITY 20 WATTS/IN.^{2}
ON-TIME 4 SEC.

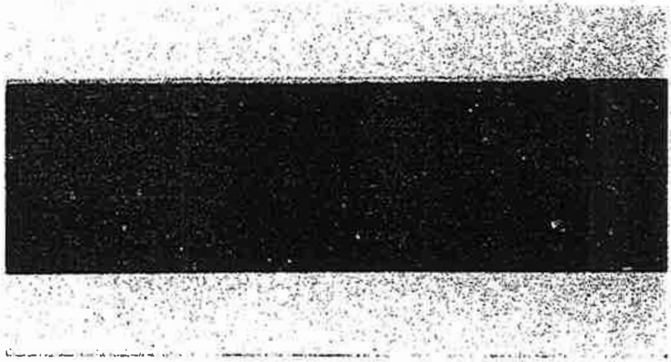


(c) ABNORMAL RUNBACK CAUSED BY EXCESSIVE HEAT-ON TIME
FLIGHT C6-5

CORRECTED AMBIENT TEMP. -6.6°C
POWER DENSITY 30 WATTS/IN.^{2}
TIME IN ICING 6 MIN.
2 DE-ICING CYCLES AT 10 SECONDS
ON-TIME

EXAMPLES OF CHORDWISE SHEDDING





CORRECTED AMBIENT
TEMP. -8.7°C

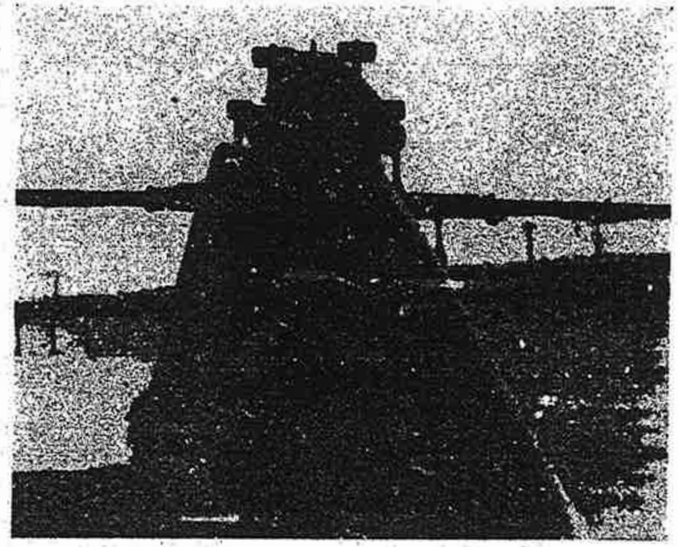
L.W.C. 0.1 GM./M.^{3}

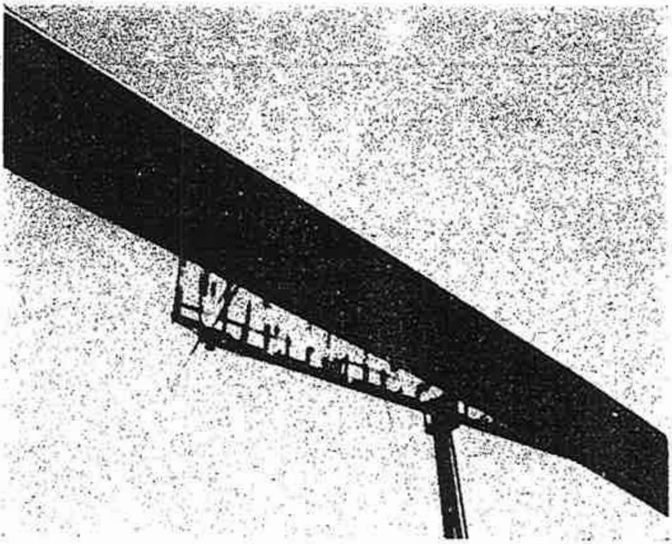
DROPLET SIZE 30
MICRONS

TIME IN ICING 10 MIN.

POWER DENSITY
30 WATTS/SQ. IN.

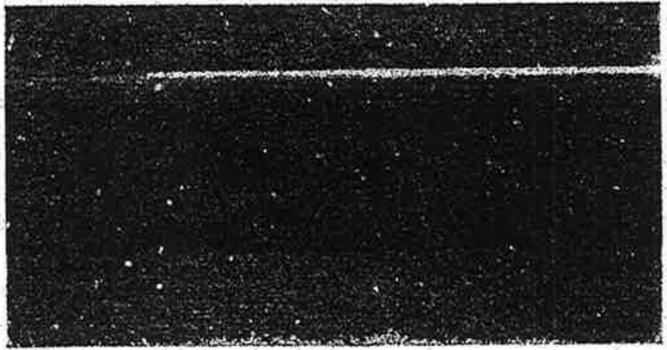
3 CYCLES OF 10 SEC.





SPANWISE SHEDDING - EXCESSIVE ON-TIME - FLIGHT S4-6

FIG. 18
LR-270



FLIGHT S4-7

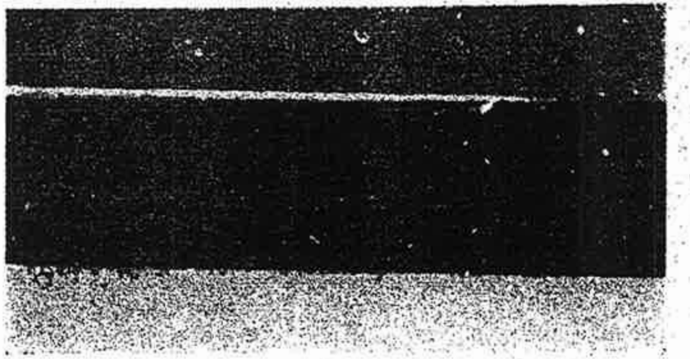
CORRECTED AMBIENT TEMP. -8.4°C

L.W.C. 0.15 GM./M.^{3}

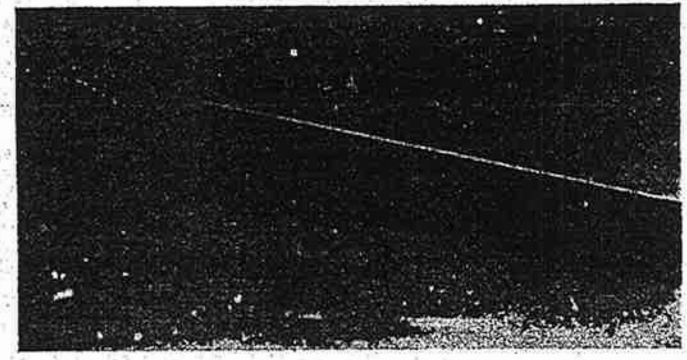
DROPLET SIZE 30 MICRONS

POWER DENSITY 30 WATTS/SQ. IN.

4 CYCLES OF 1 1/2 SEC.

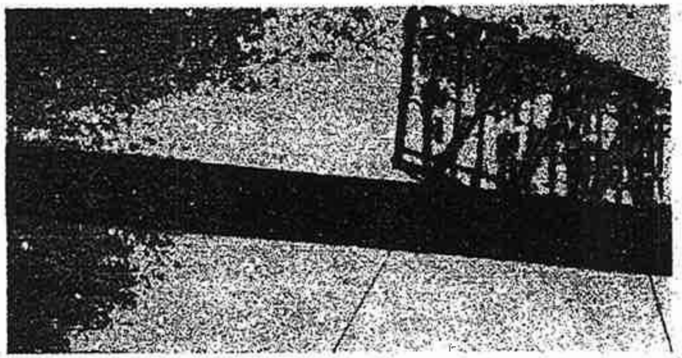


(a) DE-ICING IN THE CLOUD - 4 CYCLES OF SLIGHTLY INADEQUATE ON-TIME



(b) SINGLE DE-ICING CYCLE IN CLOUD
FLIGHT S4-8

CORRECTED AMBIENT TEMP. -8°C
L.W.C. 0.3 GM./M.^{3}
DROPLET SIZE 30 MICRONS
POWER DENSITY 30 WATTS/SQ. IN.
ON-TIME 1 1/2 SEC.



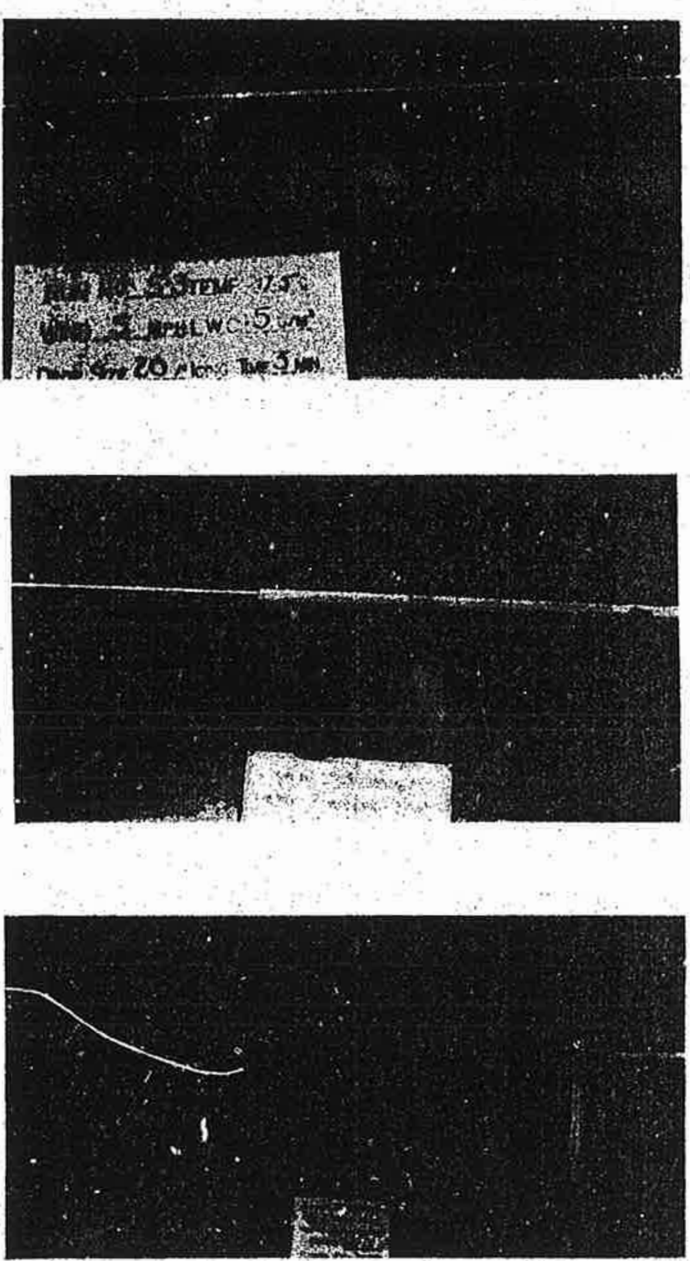
(c) SINGLE DE-ICING CYCLE OUT OF CLOUD
FLIGHT S4-9

CORRECTED AMBIENT TEMP. -7.8°C
L.W.C. 0.2 GM./M.^{3}
DROPLET SIZE 30 MICRONS
POWER DENSITY 30 WATTS/SQ. IN.
ON-TIME 1 1/2 SEC.

DE-ICING IN AND OUT OF CLOUD - SPANWISE SHEDDING

FIG. 19
LR-270

FIG. 20
LR-270

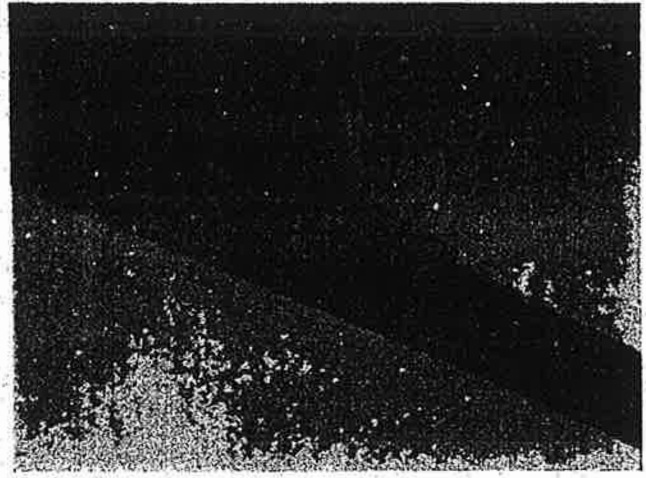


FLIGHT S5-3

CORRECTED AMBIENT TEMP. -18.1°C
POWER DENSITY 40 WATTS/SQ. IN.
TIME ON 3 SEC.

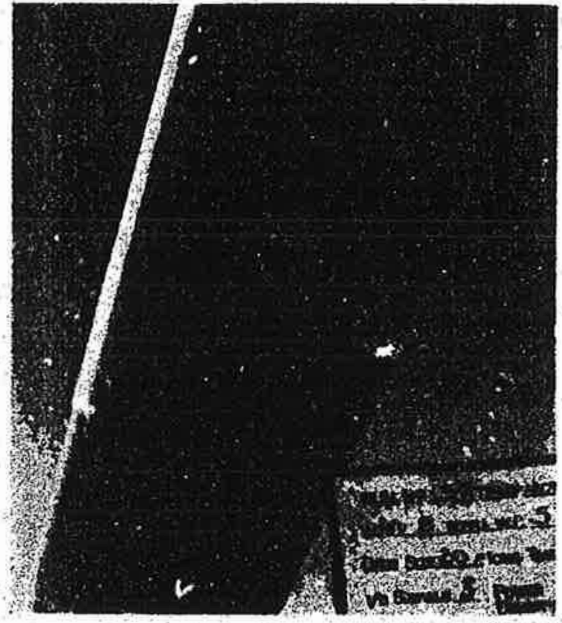
SPANWISE SHEDDING AT LOW TEMPERATURE - FLIGHT S5-3

FIG. 21
LR-270



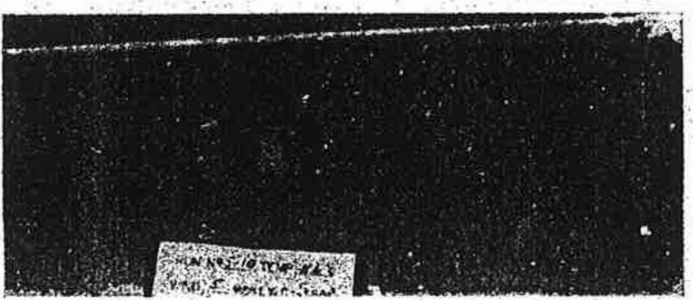
FLIGHT S2-1

CORRECTED AMBIENT TEMP. -16.9°C
POWER DENSITY 30 WATTS/SQ. IN.
POWER-ON-TIME 6 SEC.



FLIGHT S5-8

CORRECTED AMBIENT TEMP. -16.3°C
POWER DENSITY 30 WATTS/SQ. IN.
POWER-ON-TIME 5 SEC.
INADEQUATE ICE THICKNESS
RESULTING IN INCOMPLETE
SHEDDING AND RUNBACK



FLIGHT S5-10

CORRECTED AMBIENT TEMP. -16.0°C
POWER DENSITY 30 WATTS/SQ. IN.
POWER-ON-TIME 4.5 SEC.

EXAMPLES OF SPANWISE SHEDDING

APPENDIX A

ELECTRICAL FAILURE OF THE CHORDWISE SHEDDING BLADES

Upon receipt of the chordwise shedding blades it was found that the heater for area 1 (see Fig. 3) on blade A2-1 had a resistance considerably higher than the others (Table A-1), which indicated a flaw in the heater circuit. Since time was limited and the other blade was intact, it was decided to proceed with the tests using the de-icing performance of blade A2-2 for plotting the results. In this way the effect of the lower power density on the one zone of blade A2-1 was eliminated. The flights of the first four days were made successfully under these conditions, but on the fifth day it was found that the resistance of area 1 on blade A2-2 had also become very much greater, which resulted in a cold area along the leading edge of the blade.

A temporary repair was attempted on blade A2-2. Upon removal of the resin over the connection to the area 1 heater element, it was found that a number of the individual wires were broken. The heater resistance was restored to normal by soldering a thin strip of brass over all of the connecting wires, and the repair was completed by covering the whole connection with epoxy resin. Tests were then continued for two more days (covering 19 individual flights), but on the first flight of the third day the complete connection burned out (Fig. A-1) which made further repair impossible and forced the curtailment of the few remaining tests on these blades. Even if the other blade could have been repaired, the test could not have been continued with only half of the rotor protected because of the danger of excessive vibrations resulting from unbalances after shedding.

The possible cause of the breakdown is believed related to the failure of the manufacturer to cover the heater connection with the stainless steel abrasion shield. As a result the exposed connecting wires on the leading edge were possibly partially broken or kinked during assembly and, in addition, they were not adequately protected for handling and operational use. This would account for the fact that, when delivered, the resistance of the affected area of blade A2-1 had changed from that measured by the manufacturer, indicating that some of the wires had broken in transit. Another possibility is that the resin used to cover the connections contained voids along the leading edge which produced hot-spots when current was applied, and caused the wires to burn out.

TABLE A-1

RESISTANCES OF HELICOPTER HEATER MATS

Chordwise Shedding Blades

Blade A2-1

Area	Resistance (ohms)
1	8.04 (at manuf.)
	9.50 (on receipt)
2	6.89
3	6.92
4	7.34

Blade A2-2

Area	Resistance (ohms)
1	7.00 (on receipt)
	8.88 (before repair)
	6.88 (after repair)
2	6.84
3	6.91
4	6.87

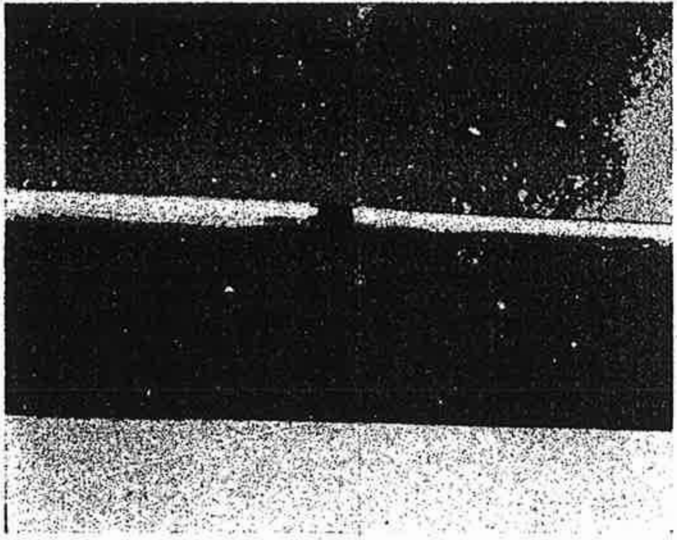
Spanwise Shedding Blades

Blade A2-413

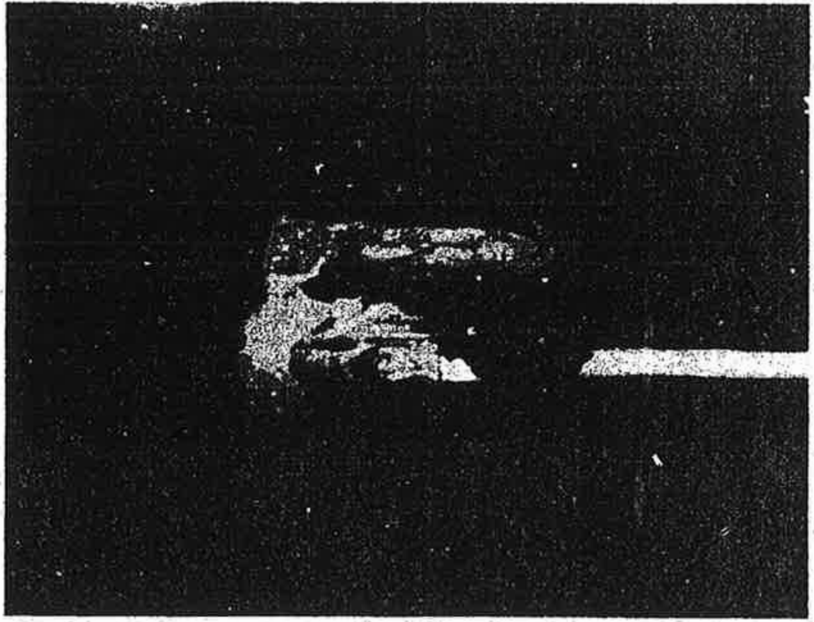
Area	Resistance (ohms)
1	8.91
2	8.69
3	8.79
4	8.81
5	8.60

Blade A2-415

Area	Resistance (ohms)
1	8.10
2	8.53
3	8.53
4	8.81
5	8.61



(a) DAMAGED AREA AT CONCLUSION OF FLIGHT C 8-1



(b) CLOSE-UP OF DAMAGED AREA

BURN-OUT OF CHORDWISE SHEDDING BLADE