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ACV ICING PROBLEMS

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INTRODUCTION

The ACV (air cushion vehicle) appears to be particularly advantageous in northern transportation owing to its ability to operate at times when and over terrain where more conventional modes of transportation are brought to a halt. One thinks particularly of the freeze-up and break-up periods of rivers and lakes and of transportation over muskeg. Unfortunately, operation under these circumstances during sub-freezing temperatures can result in the generation of a cloud of supercooled water drops which turn to ice when they impinge on the vehicle (Fig.1). Icing can also occur when operating over loose snow particles impinging on heated surfaces, melting and the resulting water flowing to adjacent cool areas and refreezing. To distinguish between these two icing mechanisms, the former will be referred to as droplet icing and the latter as snow-melt icing. Both mechanisms can present problems; however, a good understanding of the basic principles involved in these two icing processes can help considerably in predicting where problems are likely to occur and so may go a long way in arriving at design configurations that will minimize these problems.

DROPLET ICING

Droplet icing, as its name implies, results from the impingement and freezing of supercooled water droplets on surfaces whose temperature is at or below the equilibrium freezing point of the water. In the case of hovercraft operating over water, droplets are generated by the scrubbing of the cushion air as it escapes beneath the vehicle's skirt; in addition, in rough weather the action of waves and wind-borne spray (spindrift) may supplement the vehicle-generated spray. Should the air temperature be below that of the water, the droplets will transfer heat to their surroundings by convective and evaporative processes, the temperature of the smaller droplets approaching that of the air more rapidly than that of larger drops. The droplets do not immediately freeze when they cool below their equilibrium freezing temperature but exist in a metastable supercooled state. Pure water can support a maximum supercooling of about 40°C when in droplets of only a few microns in diameter, and even volumes of a

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(xx) Chairman Working Group on Icing Problems on Air Cushion Vehicles, NRC Associate Committee on Air Cushion Technology few cubic centimeters can be cooled to about $-33^{\circ}C$ before spontaneous freezing occurs[1]. However, in nature, foreign particles in the water act as freezing nuclei causing freezing to occur at temperatures much warmer than those for homogeneous nucleation; nevertheless significant supercooling still occurs, the most likely freezing temperature being in inverse proportion to the logarithm of the droplet size. Supercoolings in excess of $30^{\circ}C$ have been experienced.

Thus it is seen that an ACV operating over open water or watery terrain in sub-freezing air temperatures will produce the first prerequisite for droplet icing - an atmosphere of supercooled water droplets. Next, the trajectories of the droplets relative to the exposed surfaces of the vehicle must be such that some at least of the droplets will impinge on the vehicle. These trajectories appear to be highly complicated, depending on the characteristics of the vehicle itself (i.e., skirt geometry, cushion air flow and scrubbing speed, etc.), as well as on the velocities of the vehicle and the wind, and the degree of disturbance of the water surface. The result is that it is difficult to predict with any certainty where major droplet impingement areas are likely to be, and all but impossible to estimate rates of icing. However, a knowledge of the behaviour of droplet trajectories in the vicinity of solid obstacles can tell us much in a qualitative way about icing distribution on a vehicle.

As droplet laden air approaches a solid object, it is deflected, with the result that the droplets, the inertia of which tries to maintain them in a straight line motion, are acted upon by an aerodynamic drag force tending to deflect their trajectory. Because of this deflection, some of the drops that under straight line motion would have impinged on the obstacle follow a trajectory that clears it. Thus the actual impingement or catch rate is less than the potential catch rate assuming straight line motion; the ratio of actual to potential catch is known as the catch efficiency or collection efficiency[2]. In general, the collection efficiency is greater for larger drops and higher velocities, but decreases as the size of the object increases.

When the supercooled droplets strike the cold obstacle, it acts as a nucleating agent to initiate freezing so that, depending on the initial supercooling of the impinging water and the various heat losses and gains at the icing surface, some or all of the impinging water freezes in its immediate area of impingement[3]. The proportion that does actually freeze on impact is called the freezing fraction n, while the remaining fraction $(1-n)$ flows away from its impingement zone under the influence of gravity or of aerodynamic forces. Some of this run-off will flow over areas of heat loss where further freezing will occur, while some may actually flow or be blown completely off the surface.

DROPLET ICING Cont.

When the droplets freeze completely at their point of impact (i.e.,n=1) the resulting ice formation is highly porous and consists of numerous rime fingers extending from the iced surface. At the other end of the scale, when considerable free water exists at the icing surface, a smooth transparent ice, known variously as clear, glaze or black ice, results. Between these two extremes of rime and glaze ice, a whole gradation in the appearance of the ice exists, the greater the freezing fraction, the more air is entrained in the resulting ice and the whiter its colour while at the same time (on smaller objects at least), its shape is more tapered.

SNOW-MELT ICING

In the same way that a hovercraft operating over water creates around itself a cloud of water droplets, so when operating over loose snow a cloud of snow particles is produced. However, the concentration of snow particles that may be lofted in this way can considerably exceed that of water droplets as there is no surface tension energy to overcome. Fortunately, though, there is usually only a limited thickness of loose snow, so that a hovering vehicle is soon in the clear.

The trajectories of the snow particles behave in the same general manner as those of water droplets, except that because of their greater drag/weight ratio, their collection efficiencies are less than those of water droplets of the same mass.

Dry snow particles will not adhere to dry, sub-freezing surfaces on which they impinge, hence areas of particular significance as far as droplet icing is concerned are seldom a problem in snow conditions. Prerequisites for a snow problem are either a source of heat or the presence of free water[4]. In the first instance, ice particles impinging on a heated surface will either partially or wholly melt producing a water film which may refreeze downstream. Any free water present, such as the water film just mentioned or the presence of water spray mixed with the snow, will act as the "glue" required to adhere the snow particles to the surface.

ICING PROBLEM AREAS

Two regimes of operation need to be considered, hovering and forward motion. In forward motion, the cloud of spray generated tends to be left behind and little or no icing problem is exper-

ICING PROBLEM AREAS Cont.

ienced by smaller vehicles. Larger vehicles, however, because of their greater length do tend to envelop their after areas in spray with a result that propulsion units and directional control surfaces suffer the effects of icing. In hovering and in slow forward motion below hump speed, and also while stopping, turning, or running downwind, the cloud of spray can completely envelop the vehicle causing virtually the whole craft to accrete ice. This then is the more serious mode of operation where icing is concerned.

Where and how, then, does this ice accretion cause problems? The most immediately apparent problem is the loss of visibility resulting from even the thinnest coating of ice on the windshield and other transparencies. Perhaps the next most serious problem is the added weight of the ice, which can very quickly overload a smaller vehicle. Other areas where problems may occur on particular types of vehicles are: (1) the jamming of hinges due to ice on control surfaces (Fig.2); (2) the icing and jamming of control linkages, cables, etc.; (3) the icing of engine intakes (particularly gas turbine engines) with the consequent danger of ice ingestion; of particular seriousness is the icing of engine air filters, the purpose of which are to prevent droplet erosion of the compressor blades, and the icing of foreign object screens; (4) the icing of guard screens ahead of propulsion and lift fans; (5) the icing of deck stores and cargo and their tie-downs (Fig.1).

Skirts appear to present little problem due to their flexibility, and their closeness to the water (little supercooling of the impinging water). However, cases have been reported of snow packing in skirt sections. Snow may also result in icing within the plenum should there be any sources of heat present; however, little obstruction to air flow is thought likely.

Fans and propellers tend to be somewhat self-protecting by virtue of the centrifugal loading on the ice. However, because propeller speeds tend to be lower than those of aircraft, greater masses of ice are likely to be shed, resulting in probable imbalance and a damage potential from the thrown ice. Similar problems apply also to centrifugal blowers, but their less critical aerodynamics is in their favour.

SOME GENERAL DESIGN RULES

Bearing in mind the basic principles of icing that were reviewed above, and particularly the effect of the dynamics of the droplets on the collection efficiency, certain rules of good icing design can be enunciated.

SOME GENERAL DESIGN RULES Cont.

Of major importance is the inverse relationship between the collection efficiency and the size of the collector. The effect of the larger initial ice growth rate resulting from this, combined with the greater relative spreading of unfrozen surface water results in a relatively much wider ice accretion on a smaller collector than on a larger one, and so presenting an ice collection surface that grows at a faster rate the smaller the collector. This effect is demonstrated in Figure 4, which is taken from some simple experiments made at NRC on the icing of cylinders . A 1½" diameter cylinder had its effective width increased by ice some 3 to 4 times (depending on temperature) in one hour under the particular conditions of the test, while that of an 18" cylinder was increased only by a factor of about 1.05. The result of this on the weight of ice caught is shown in Figure 5; in particular it should be observed that a 12-fold increase in basic cylinder diameter from 1½" to 18" resulted in only a 3-fold increase in the amount of ice accreted in the one hour period.

The obvious conclusion to be drawn from all this is that the number of small scale ice collectors, such as handrails, support struts, rigging, etc., should be reduced to a minimum and where complete elimination is not feasible one larger scale component should be made to serve the function of several smaller scale ones (Fig.3). In other words, the external design should be as "clean" as possible.

Deck cargoes (Fig.1) should not be left uncovered, or lashed down with rope netting, but should be completely covered over with an impervious cover such as a rubberized tarpaulin from which ice will detach quite readily when flexed. Tie-downs for such a tarpaulin may still present a bit of a problem, but plastic encapsulated ropes are available from which ice can quite readily be removed. Bollards are preferred over rings or small cleats for tie-down points. Similarly, inflatable life raft containers (Figures 1 and 3) may also be more readily released from their cradles and launched if they are covered over with such rubberized canvas.

Some alleviation of the windshield icing problem may be obtained by placing the control cabin as high as possible and amidships, in this way, few of the larger drops in the spray will reach this critical area. However, this solution may introduce other and worse problems because of the additional structure required and the provision of a companion ladder to reach the cabin (Fig.3). Such a ladder, being a fine ice collector, should be enclosed within the cabin structure or other wise shielded from droplet impingement.

SOME GENERAL DESIGN RULES Cont.

Control rods, cables, linkages, etc., whether for the engines or control ports and surfaces should be totally enclosed, perhaps below the deck surface, but where of necessity parts have to be exposed, the use of rubber boots over hinges, sliding surfaces, etc., can be most helpful.

In the case of gas turbine engine inlets, aircraft practice will in most cases suffice. However, the air flow patterns, and hence the droplet trajectories, in an actual installation should be checked for conformation with those of the icing test cell installation. Otherwise the icing test results may be invalid and further icing tests using the actual installation geometry may be necessary. The best primary safeguard against ice ingestion problems is a rugged engine.

Where protective screens ahead of fans and propellers are provided solely to prevent injury to personnel, such screens must have a considerable open area to minimize the possibility of blockage and unacceptable pressure drop due to ice on the wires. Such screens should, therefore, be placed at least an arm's length from any moving parts to fulfil their intended purpose. A mesh dimension of less than 6" cannot be recommended.

Screens which are provided for foreign object damage prevention may themselves become a source of foreign objects (i.e. ice) after an icing encounter quite apart from problems associated with the pressure drop resulting from the iced screen. Such screens are, therefore, not recommended and greater efforts should be made either to eliminate the sources of foreign objects, or where this is impractical (due to the sources being external to the vehicle) to provide means of deflection upstream of the engine or fan inlets.

For operation in snow, it is essential that sources of stray heat to critical surfaces be eliminated. Such critical areas are likely to be in or ahead of engine and fan inlets, or close to controls or other moving parts vulnerable to water ingress and subsequent freezing.

PROTECTIVE MEASURES

Good basic design can do much to reduce the icing problem but cannot in itself eliminate it, so that certain protective measures and operational procedures may still be found necessary.

PROTECTIVE MEASURES Cont.

Icing problems may largely be avoided, where operational requirements permit, by crossing open water areas at high speeds and restricting manoeuvring and hovering to ice covered areas or dry land. However, extensive high speed operation over open water will eventually cause significant icing particularly if the water is at all rough.

As stated earlier, when icing occurs the most immediate problem is that of visibility through the transparencies of the control cabin. A number of solutions are available for this problem, the most desirable and effective being the use of electrically heated windows. These windows, employing a transparent gold film, are available in both glass and plastic, and good temperature control is achieved using an embedded temperature sensor. Even with their use, some care is required in their mounting arrangements to avoid problems resulting from the freezing of run-off water. Power ratings are expected to be in the order of 150 watts per square foot, and total system cost of about $500 for an area the size of a standard truck windshield.

For smaller vehicles, the use of alcohol spray in conjunction with windshield wipers can give acceptable visibility within the swept area of the wipers. A hot air blast on the inner surface of the transparency, although perhaps the most easily implemented solution, is not the most efficient and may result in damage to the transparency besides causing discomfort to the operator.

For flat areas or for surfaces with simple curvature, an effective method of ice removal is the use of rubber pneumatic de-icers such as have been used on low speed aircraft for many years. Such de-icers might well be used on fin leading edges for instance, and other forward facing vertical surfaces subject to heavy icing, but are not suitable for working deck areas because of the damage they may sustain.

On smaller vehicles whose deck areas are frequently of fibreglas and relatively flexible, ice can be readily removed by an impulsive deflection of the surface (i.e., by banging it). This leads to the idea of applying a deflection periodically while in icing conditions by a device located beneath the deck and operated by the pilot.

For larger vehicles having metal decks, an electro-impulse method of de-icing developed in Russia appears feasible and attractive[6]. This method employs a series of inductors mounted behind the surface to be de-iced and impulsively energized periodically by connection to a charged capacitor. The impulse so applied to the metal structure results in failure of the ice bond at the surface. The

PROTECTIVE MEASURES Cont.

system is said to be lighter and more economical in electrical energy than a conventional electro-thermal de-icing system.

A word of caution on the use of thermal anti-icing systems must be given. This applies to operation in dry snow conditions, for should anti-icing systems be employed under these conditions, the additional thermal energy required to supply the latent heat of fusion may exceed the system capacity and result in ice formation[4]. A safe rule to follow when operating over loose snow is to turn off all thermal anti-icing systems, i.e., windshields, engines, engine inlet ducts, etc.

CONCLUSIONS

It is apparent that icing is a serious operational problem for air cushion vehicles in water/ice interface conditions. This paper has attempted to give in a qualitative way some idea of the physical processes involved in the icing phenomenon, so as to give the designer a better grasp of what he is dealing with and so allow him to avoid or minimize possible problem areas. Some possible methods of icing protection have been suggested.

It is to be expected that as more operational experience in icing conditions is logged, more definite guidelines on design principles and protective measures will be possible.

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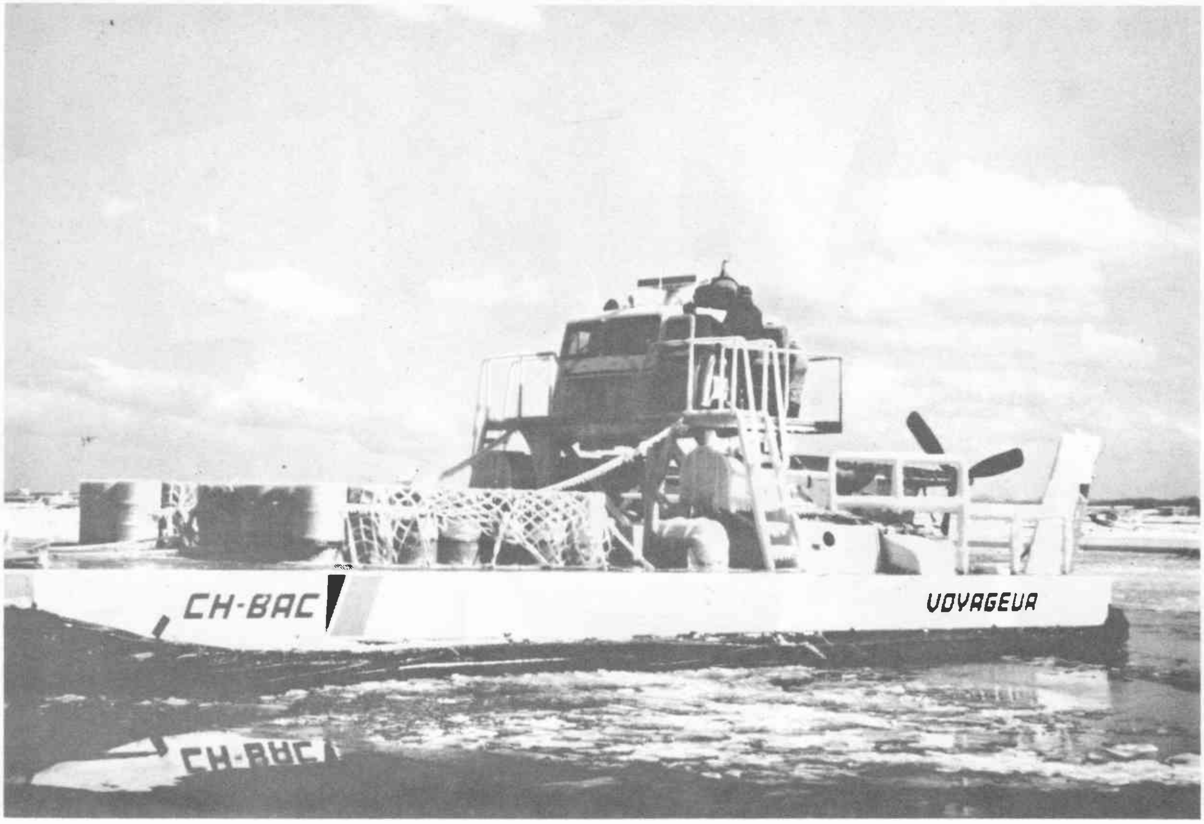

FIG. 1 BELL AEROSPACE CANADA "VOYAGEUR" AFTER WINTERTIME OPERATION OVER WATER

By Permission

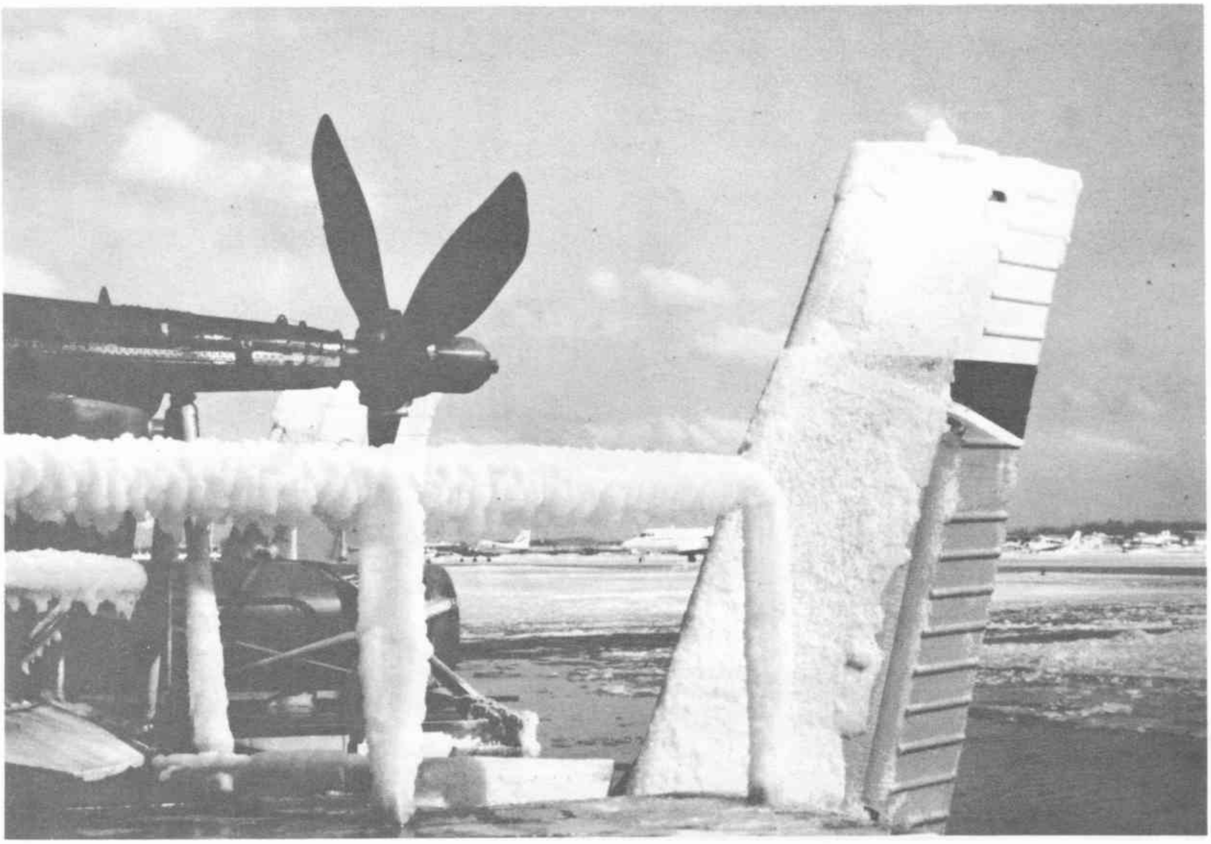

FIG. 2 ICING OF HANDRAILS, CONTROL SURFACES
AND PROPELLER
BELL AEROSPACE CANADA "VOYAGEUR"

By Permission

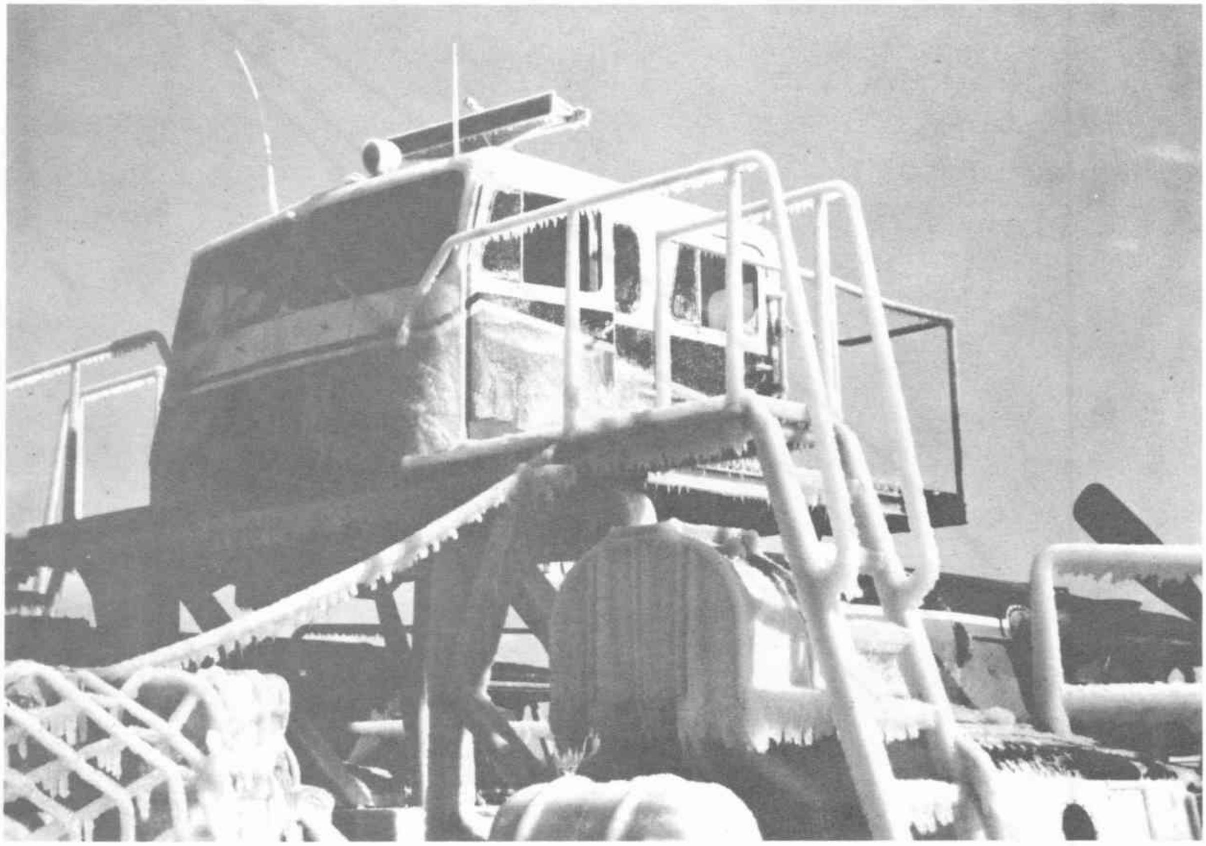

FIG. 3 ICING OF VARIOUS "CLUTTER"
BELL AEROSPACE CANADA "VOYAGEUR"

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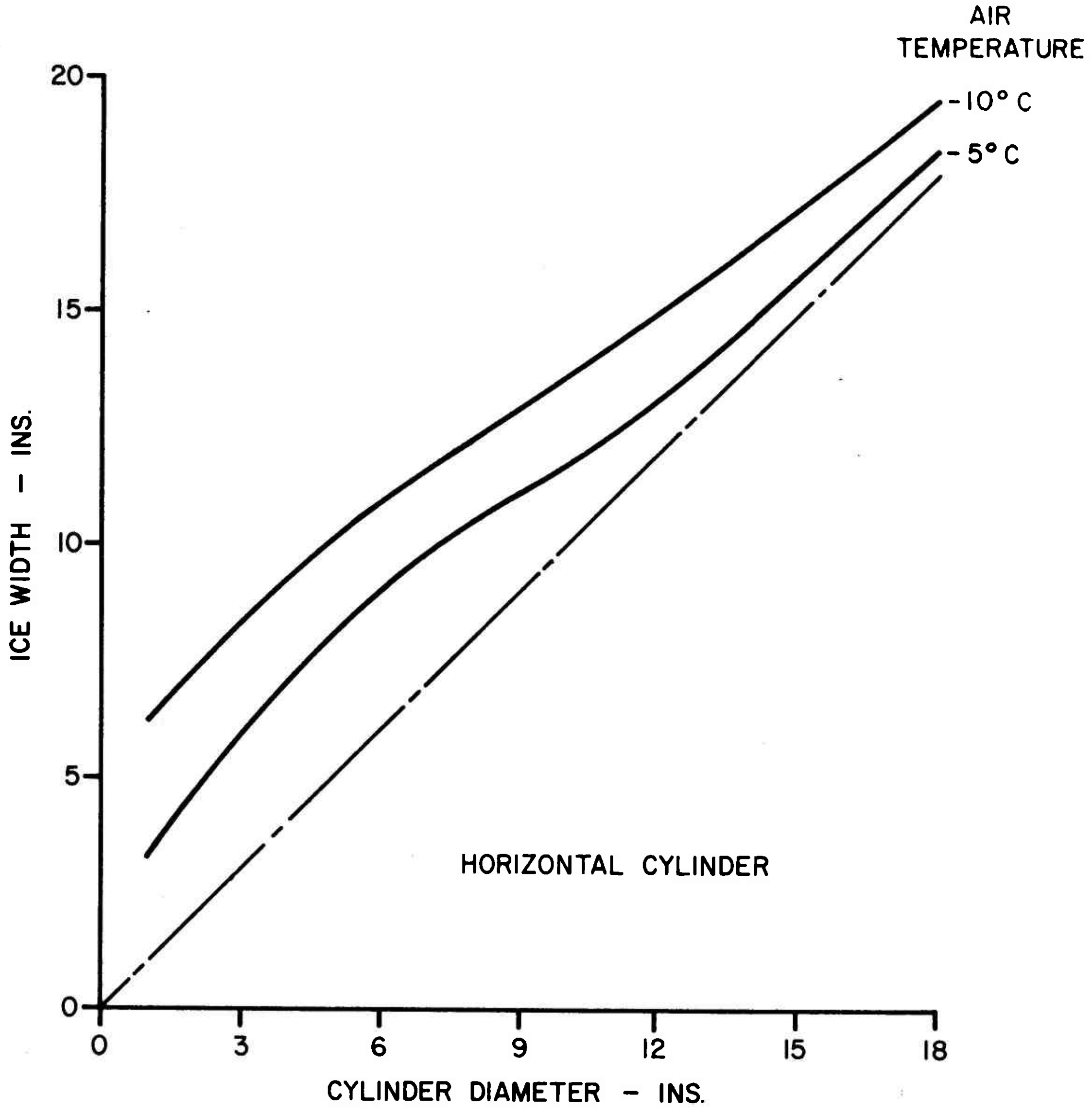

FIG.4 EFFECT OF CYLINDER DIAMETER ON FRONTAL WIDTH OF ICE AFTER 1 HOUR

VELOCITY:	50 mph
WATER CONCENTRATION:	3.2 g/cu. m
DROP SIZE:	0.2 mm (MEDIAN VOLUME DIAMETER)

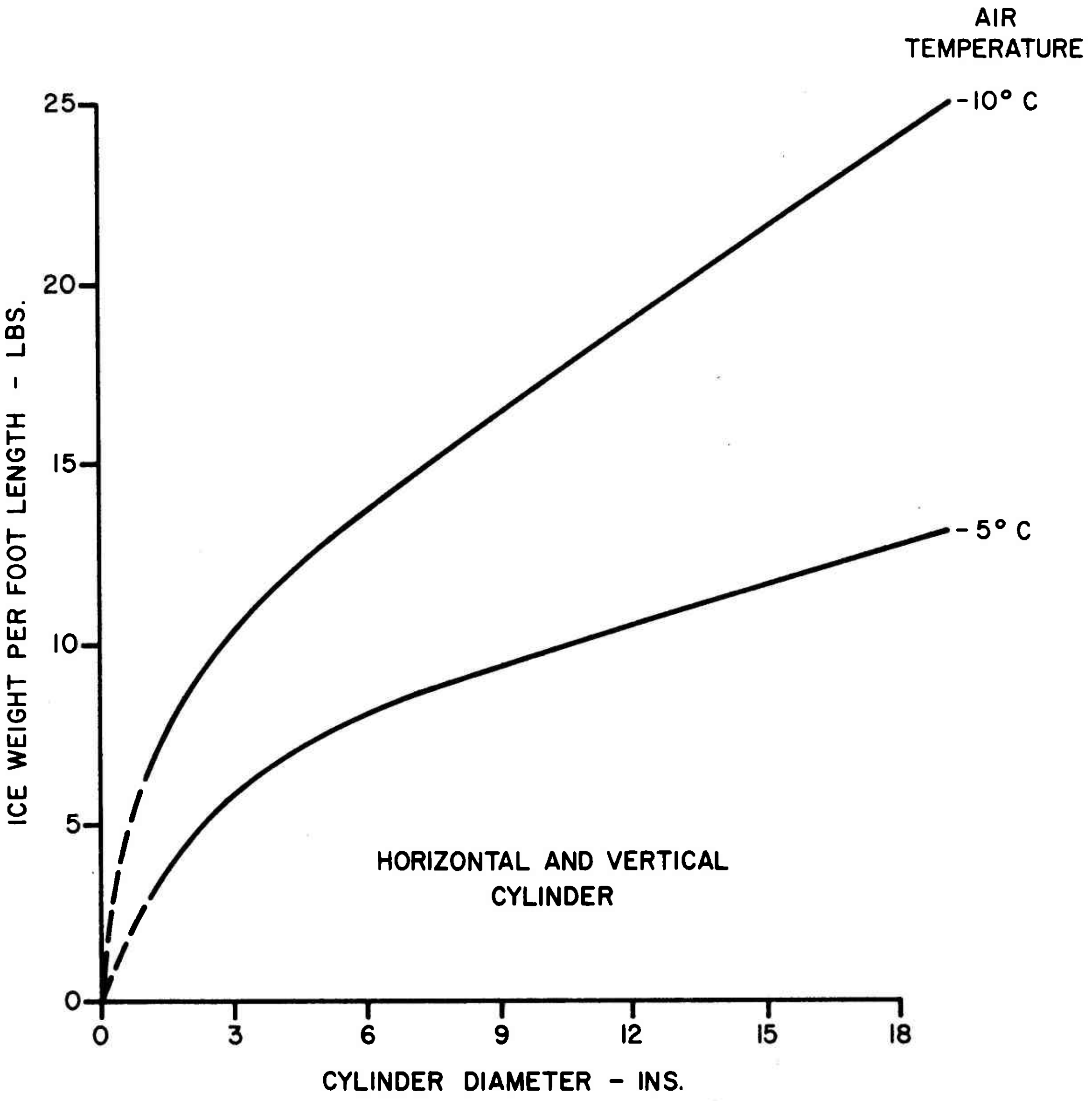

FIG. 5 EFFECT OF CYLINDER DIAMETER ON WEIGHT OF ICE ACCRETED IN 1 HOUR

VELOCITY:	50 mph
WATER CONCENTRATION:	3.2 g/cu. m
DROP SIZE:	0.2 mm (MEDIAN VOLUME DIAMETER)