northern co-ordination and research centre department of northern affairs and national resources

AIR-CUSHION VEHICLES IN THE CANADIAN NORTH

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NCRC-65-3

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by

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Northern Co-ordination and Research Centre,
Department of Northern Affairs and National Resources,
Ottawa.

August, 1965.

I

During the past eighteen months air-cushion vehicles have been demonstrated over a variety of terrain : salt marshes, the sands of the North African desert, the ice floes of the Baltic in February, and the snow on the Greenland ice cap.

Such versatility in what was originally conceived of as only an over-water vehicle leads to speculation on their suitability as a means of transport in the Canadian North. This report surveys existing sources of information to bring together as much material as possible which bears on this matter. As will be seen, with present knowledge we cannot attempt to answer the basic question of the vehicle's practicability. We shall, rather, aim at two simpler goals: first, to show areas of operation, either existing at the present or foreseeable, in which air-cushion vehicles would offer advantages over those presently used ; second, to examine these proposed uses more closely to see what difficulties we can anticipate and what lines of further inquiry might be profitable.

The first question we must ask is, bluntly, whether air-cushion vehicles (the less formal and widely used "hovercraft" strictly applies only to those craft with peripheral jets, such as the Westland series) have any real use whatsoever. What can they do that more well-known methods of transport, in particular aircraft, cannot? It is frequently said that the development of the Arctic has rested on the use of aircraft and helicopters ; for example, one expert on the subject writes that

"It was the increasing speed of aircraft even more than their increased range which enabled man to secure a measure of travel mastery over the 'cold forbidden areas of the earth'" (Stewart, 1964 : 398). Furthermore, there already exist a great variety of other vehicles : ships can convey heavy cargoes to many places in summer, oversnow vehicles are useful for local work in winter, and there is the possibility of building roads and railroads wherever needed. Used in combination, these should be able to give any support needed to settlements or scientific parties. Perhaps adding another type of vehicle to an already long list serves no real purpose.

One answer to this is that there are certain types of surface (shallow water with thin ice is an example) over which we might have reason to travel and with which no existing machine can readily cope. Similarly, many jobs in the North, such as the support of small scientific groups or trips to the smaller settlements along the Mackenzie River during break-up and freeze-up, can only be done by helicopters at present. The jobs do not always require the great mobility such machines offer; we should be on the lookout for a vehicle which would be adequate for the operation and might do it at less cost.

This problem of cost is of over-riding importance in northern development. In the southern parts of Canada the difficulties of finding means of transport are less acute; we have had trains, trucks, and ships, all contributing to cheap development of the land. As we go north we first cross a broad region of the continent where distances, terrain, and climate are such that the expense of building and maintaining year-round roads is virtually prohibitive without guaranteed large, long-term returns; farther north lies the arctic archipelago, where, in the most favourable parts, ships can operate for maybe two to three months a year, while in many regions they cannot operate at all.

Aircraft can surmount such problems, whether those of road-building and maintenance or those of ice-clogged channels, but at the expense of economy. Comparisons, except on the most detailed basis, are frequently misleading; it is, nonetheless, instructive to note that heavy duty trucks - a large tractor and semi-trailer or a ten wheel diesel dump truck - can haul loads at rates of about 130 ton-miles per gallon,[1] while a low power European car can carry loads at about 25 ton-miles per gallon. In comparison, an Otter hauls at about 5.7 ton-miles per gallon and a C-130 "Hercules" at about 8. This comparison, admittedly, is the most rudimentary possible and probably grossly unfair; it does show the great advantage of surface vehicles, given a suitable route on which to travel, over aircraft.

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1. This estimate is for a truck like a Mack type B-81 carrying 14 cu. yds. of sand or a tractor like the Mack 609 series with a semi-trailer with a 20 ton load; the mileage obtained per gallon of fuel is obviously highly variable. That used here reflects driving conditions on paved roads in fairly level country.

Air-cushion vehicles might have the ability to operate over much of the terrain of the North and do it more economically than aircraft; they might form a suitable carrier for preliminary stages of development before it was practical to build roads; they might be able to travel through the frozen channels of the archipelago. These are general reasons for the study of the potentiality of air-cushion vehicles in the North; we have also seen that there are, even now, particular jobs for which they might be especially suitable. Let us, therefore, turn to a more detailed outline of the properties of these machines which might be advantageous or troublesome in northern work.

Air-cushion vehicles are surface vehicles which can combine an amphibious nature with some speed. As mentioned above, the original design was that of an over-water craft which, for the size of vehicles now being built, would have had a clearance of the order of several inches. This was changed by the development of so-called "flexible skirts" - curtains of rubber and fabric which help to contain the air cushion but which are designed to give way and allow the vehicle to go over an obstacle. These have increased the effective ground clearance to 3 ft. 6 in. or more even for craft of a modest size. On water, this means that they are able to travel over much rougher seas than originally expected; on land, it puts them into competition with other surface vehicles for travel in flat regions or over snow and ice. We shall see below that present vehicles have adequate clearance for much work in the north of Canada.

Stripped of the complicating details necessary for stable travel, the type of air-cushion vehicle considered here can be pictured as a platform placed on top of the flexible rubber skirt to form an air reservoir shaped somewhat like the top of a pillbox. A fan on the platform blows air into this reservoir until the pressure inside is high enough to lift the vehicle off the ground and allow the air to escape around the bottom edge of the skirt.

From this picture we can see two of the advantages of air-cushion vehicles. First, in case of engine failure, they are safer than a light aircraft or helicopter. The reservoir of air holding the craft up leaks away comparatively slowly; the vehicle settles onto the surface and comes to rest. It can be built light enough to float on water; as tests in Greenland have shown.[1] Emergency stops can also be made on snow, from speeds of at least 30 mph. without damaging the underside of the vehicle.

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1. G. Abele, U.S. Army Material Command Cold Regions Research and Engineering Laboratory (CRREL) private communication. The vehicle used in these trials was the Bell Aerosystems "Carabao", a small (ton-and-a-half) craft riding on three plenum chambers at an effective ground clearance of 18 in.

Second, if the craft is sufficiently large, it can be designed to be more economical of power - and hence of fuel - than an aircraft of similar capacity. To support the vehicle, the fan need only maintain the cushion pressure; in principle, the power necessary to do this is determined by the leakage rate at the lower edge of the skirt. This rate depends on the dimensions of the leak - its length, or the perimeter of the craft, and height, or the ground clearance - and on the internal cushion pressure which, in turn, depends on the overall loading (weight per unit area) of the craft.

Suppose we keep the cushion pressure and the ground clearance the same, but multiply all linear dimensions of the vehicle by some factor. The allowable load for our cushion pressure increases as the area, or as the square of the scaling factor, while the amount of air lost only increases (other things being equal) as the perimeter of the vehicle, or as the scaling factor itself. The relatively small air-cushion vehicles available at present are quite closely competitive with aircraft of a similar size; we should expect, as designs in fact show, that larger craft would be considerably more economical.

If we keep the cushion pressure as low as possible we have the least loss of air and need the least power to support the vehicle. Another advantage of low cushion pressures is that the vehicle is then of the so-called "low pressure type" which is necessary for operation over muskeg or soft snow. A rule of thumb is that for such a use a vehicle should have a bearing pressure below 4 psi. Typical tracked vehicles vary in this respect from between 1.7 and 2.0 psi (the various Nodwell vehicles) to the 4.1 psi of a D-8 tractor (the usual prime mover used by the U.S.A. in Greenland and Antarctica) (Mellor, 1963). Present hovercraft designs have bearing pressures which are typically ten times lower--in the range 0.22 to 0.49 psi. Thus, in addition to travelling over water, land, or ice, we should expect air-cushion vehicles to work well on snow and, of interest in the present connection, it should be able to travel easily over mixtures of thin ice and open water.[1]

Set against these desirable qualities are several factors which might cause considerable trouble in northern operation. These arise from the very principle of the air-cushion vehicle: the reduction of the frictional drag on the ground on the machine to as low a value as possible

The first difficulty that this causes is a certain lack of maneuverability. Without touching the surface, it is difficult to make tight turns. Similarly, without some device like a keel, the vehicle has a tendency, in cross winds or in turns, to proceed like a crab - i.e. with a large yaw angle. There is considerable difficulty in traversing a

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1. The tests of the "Carabao" in Greenland in July 1964 showed its abilities on snow, at least the fairly dense snow found there. Questions can, of course, be raised about how these machines would behave in deep soft snow, but this is of little interest in the present connection.

slope, since the craft always has the tendency to slide sideways down-hill.[1] Going straight down-hill without brakes is a nuisance; in the Greenland trials this was done by periodically turning the craft around so that it was going backwards down the hill and then using the forward thrust of the propulsion unit as a brake.

Most of this means that air-cushion vehicles are not designed for steep, mountainous country. Still, the need of an effective braking method and of something in the way of a keel to enable the vehicle to traverse mild slopes is basic. The Bell "Carabao" machine has used so-called "harrow disc" attachments to help in this last respect. They consist of two steel plates mounted slightly to the rear of the center of gravity, and were moderately successful in Greenland, although it was clear that there was room for considerable improvement.[2]

We should expect certain conditions in northern Canada (for example, following a tortuous route through heavily hummocked ice) in which a lack of ability to make sharp turns would cause difficulty. Two solutions to this problem are presently available: going at reduced speed or "dragging one's skirt" or some other device. The latter brings up the technical

1. This, obviously, is not the same thing as hill-climbing ability, which depends merely on the skirt height and the amount of thrust power available. Some designs can go up steep hills: for example, the Westland SR. N5 can go up short hills of a slope of 1 in 3.

2. G. Abele, private communication.

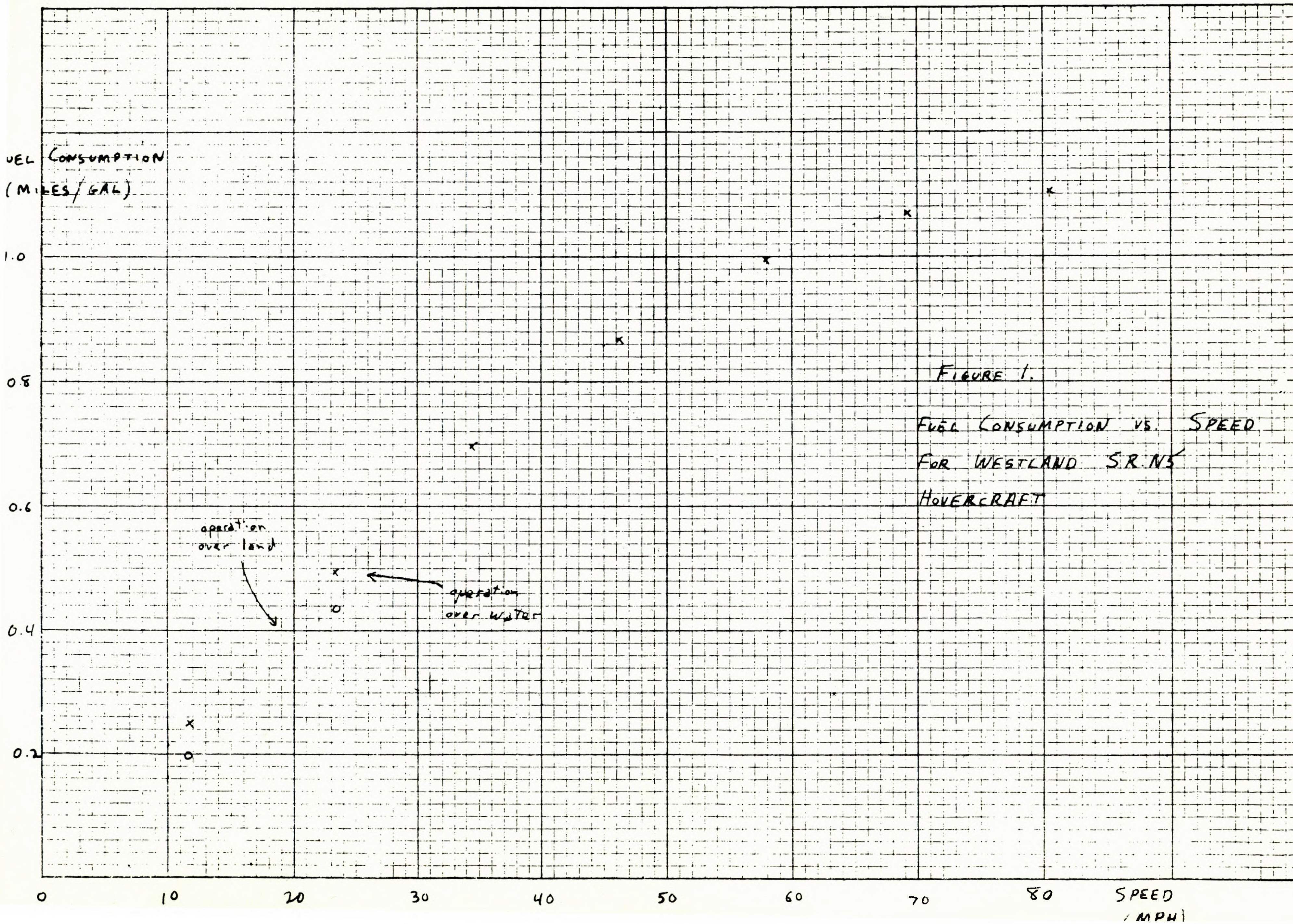

FIGURE 1.

FUEL CONSUMPTION VS. SPEED FOR WESTLAND SR.N5 HOVERCRAFT question of skirt wear, which will be discussed in the next section; operation at reduced speed raises two problems: unexpected grounding (to which we shall also return later) and excessive use of fuel.

Conventional surface vehicles, such as cars or trucks, use roughly the same amount of fuel to go a given distance regardless of their speed. This is not true of an air-cushion vehicle; again, this is a consequence of the desire to cut the ground friction down as far as possible. As a result, we find that at 60 kts, the power needed to propel an air-cushion vehicle is of the same magnitude as that needed to lift it. At lower speeds, we of course need less propulsive power, but the lift power required actually increases somewhat, because of the loss of aerodynamic lift. Thus as we go more slowly we need more fuel to cover the same distance; Figure 1 shows the magnitude of this effect for the Westland SR.N5; (Dickenson, 1964). In practical terms, this means that an air-cushion vehicle cannot afford to go unexpectedly slowly over long distances. This fact may be of great consequence in using it on routes where there might be unforeseen obstructions to visibility or rough stretches.

In summary, we have the following basic features of air-cushion vehicles to bear in mind in analysing their potential utility:

1. They seem able to traverse an amazing variety of terrain at speeds up to 60 kts or more. By their nature, they are best suited to lands of gentle relief. Present designs can pass over small scale

irregularities (rocks, ridges of ice, and so forth) up to 3 ft. 6 in. or 4 ft. high; what we can expect in practice is a matter to examine at some length.

2. They offer the conventional advantages of surface vehicles over aircraft: greater safety and, at least in the larger sizes, more economical operation.

3. On the other hand, we have, with present designs, a lack of precise maneuverability. This, coupled with the fact that slow speed operation leads to increased fuel consumption for the same distance, could be of concern in many situations; an example is going over an unfamiliar route with only isolated fuel caches.

In the remainder of this report we give a more detailed analysis, so far as it is possible from the materials at hand, of the suitability of certain types of operation for air-cushion vehicles. Here we obviously have to particularize. We must decide on typical routes where a hovercraft might be useful and on the conditions under which we should want to use it. It is obvious that, given any type of vehicle, we can select conditions which make using it extremely easy or virtually impossible; the following outline is an attempt to produce a balanced set of circumstances of differing difficulty against which we could measure the utility of air-cushion vehicles.

At the present time, fairly small machines are available - they compare with helicopters or light aircraft. We have already mentioned situations where they might be useful: the provision of year-round service to the smaller settlements on the Mackenzie or of support to maintenance or other groups in the area. Farther north, they might be used in place of helicopters to supply certain types of small scientific parties.

A larger machine might form a means of supplying various points in the Arctic. To be specific, we shall consider two situations: a route from Churchill to Cambridge Bay or Coppermine, via the west coast of Hudson Bay, then going overland to Chantrey Inlet or Sherman Basin and the channel along the north coast of the continent. This would exploit the amphibious abilities of the vehicle and also provide a considerable saving in distance over the present surface route down the Mackenzie. Second, we shall consider a route in the northern part of the archipelago: that from Resolute to Mould Bay. The distance between these points is about 500 miles; for present vehicles, with a range of about 250 miles, this would involve fuel caches en route, but it might not be unreasonably great for a larger vehicle.

We must also decide on the times of year during which we would expect to use these vehicles. Most favourable conditions occur in the summer; to be of any real value, however, a machine must be capable of year around operation. Especially in the Arctic, this brings up the rather prickly question of night operation - a field on which much practical information seems to be needed. For simplicity we shall limit

Table I

Comparative Vehicle Characteristics

	Aircraft				Air-Cushion Vehicles			Helicopters	
	Otter	Caribou	C-130-E "Hercules"	CC-4	SR.N3	SR.N5	SR.N6	Sikorsky S-61-R	Boeing Vertol 114
Payload (lb)	2100	8740	45000	1200	28400	3300	6500	5000	10455
Fuel Capacity (Imp. gal.)	178	690	8070	40	940	265	265	555	515
Cruising Speed (mph)	138	182	345		65	65	60	142	150
Range	875 (45 min reserve)	242 (45 min. reserve)	2530 (5%res. 30min. cruis.)		250	250	250	500 (10% reserve)	226
Total Engine Horsepower	600	2900	16200	200	4200	1050	1050	1050	2500
Ground clear-anee	-	-	-		4 ft 9in	3 ft 6 in	3 ft 6 in		-

ourselves to surveying the various types of surfaces and weather conditions that occur through the year and shall only offer a few comments on the added problems of operating the hovercraft at night.

In short, we shall study the conditions to be expected, at different seasons, in the following areas:

1. along the Mackenzie River;

2. among the islands of the arctic archipelago; more specifically, along the route from Resolute to Mould Bay and along the northern coast of the continent from Chantrey Inlet to Cambridge Bay or Coppermine;

3. on the western shore of Hudson Bay; and

4. overland from Hudson Bay (in practice, from Baker Lake or Wager Bay) to Chantrey Inlet.

We shall, of course, be interested in the precise operating characteristics of various air-cushion vehicles. At present, two relatively small vehicles are readily available: The Westland SR.N5 and the Cushioncraft CC-4. Westland is also building its SR.N6, which is a "stretched-out" SR.N5 formed by adding a middle section; they have also built a larger military machine, the SR.N3. Relevant information on all of these is summarized in Table I, together with data on comparable aircraft.

The main technical problems we could expect to encounter can be divided into three groups:

1. Those connected with the design of the machine itself. In this class we include such things as the effect of the arctic climate on machine operation, problems of skirt wear, and problems arising from slow speed operation.

2. Problems of the suitability of the surface. In the case of operation over snow and ice, what irregularities are we to expect? Similarly, if we wish to go overland, can we hope to find smooth enough surfaces that we would be able to use machines of limited ground clearance without previous preparation of the terrain? Or, as has been suggested for northern Alaska, is it necessary to form a path, or even a shallow canal, say by using a bulldozer?

3. The effect of weather on machine operation. Under this heading we include the factors, such as fog, blowing snow, or high winds, which could make vehicle operations impractical. Straight-forward cold weather and the like is included in (1) above.

In the next three sections we shall consider each of these in turn.

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1. Sources: Jane's All the World's Aircraft, 1964-1965 and Air-Cushion Vehicles (Supplement to FLIGHT International), various dates.

II

The detailed design of present air-cushion vehicles can lead to a variety of problems in operating in the North. These fall into two classes: those caused by varying degrees of cold weather and those arising from the variety of surfaces over which the vehicle would travel. In principle, all these problems are soluble, although in some cases the solution might involve a major redesign of the vehicle. In this section we shall describe as many of them as we can and try to indicate how serious each might be in practice.

Cold weather raises concern on two accounts. Any temperature below freezing can lead to trouble with icing; furthermore, the extreme cold of the northern winters can produce a great variety of difficulties with almost any mechanical object.

With air-cushion vehicles, operation over open water at temperatures below the freezing point can lead to spray freezing onto the craft and loading it down with ice. During trials of the Vickers VA-2 craft on the Baltic in February 1964 a deliberate test was made to find the magnitude of this effect. In twenty minutes' hovering over open water at 28 °F the vehicle collected an estimated ton of ice. (Dickenson, 1964: 19). This, of course, does not represent what might happen under typical operating conditions, which are considerably less favourable to ice build-up. It is, nonetheless, an obvious source of worry. There is some reason to believe that the SR.N5 might not be as liable to such icing, since a large volume of hot exhaust gases are circulated through the structure.

In Greenland, in July 1964, further tests of an air-cushion vehicle extended the operating range down to 5° to 10° F and uncovered no new problems. Such temperatures, of course, are much higher than those to be expected in most of Canada in the winter months. Still, a great mass of experience has been accumulated on operating other vehicles in extreme cold, and it is clear that the unusual problems of air-cushion vehicles in northern winters should be limited to the effect of low temperatures on the flexible skirts. -40° F is quoted (Booz-Allen, 1962: 1-85) as the temperature at which most varieties of synthetic rubber start to lose their elasticity and to become brittle; temperatures in this range are familiar everywhere in the north. -65° is a more reasonable limit to work to; this leaves us comparatively few products which we might use, such as Silicone Rubbers and certain special types of Styrene Butadiene Rubbers. (Booz-Allen, 1962: I-71, I-73). There is, still, reason to believe that this cold-weather difficulty can be overcome by suitable choice of materials, though they might be considerably more expensive that what is presently used.

The different surfaces - snow, jagged blocks of ice, raised beaches, muskeg - over which an air-cushion vehicle would have to travel in order to be really useful in the north raise more varied problems. For example, the particular design of the machine may be such that during winter operation part of it will become full of snow. This happened with the

Bell "Carabao" in Greenland. Such a situation can presumably be avoided by suitable design. As with the icing difficulty described above, it should be cured if possible, for a considerable amount of snow in the machine acts as excess load and causes reduction of the ground clearance and greater use of fuel.

Another matter of concern is skirt wear. No abrasion of the skirts was observed in Greenland after some twenty hours of testing, but this is to be expected, for the operation was almost entirely over snow, and its abrasive force must be very small. In our type of northern operation, however, the vehicle would have to cross jagged pieces of ice and limestone beaches. Small ridges on the latter might rub on the skirt and eventually cause serious abrasion; in either case we might encounter skirt damage in the form of parts of the skirt snagging on fairly large stones or sharp blocks of ice and being torn off. The seriousness of this problem can only be found by actual tests.

Although small irregularities in a snow surface, such as sastrugi, should not contribute to skirt wear, they might create a dragging force and slow the vehicle down. In Greenland the "Carabao" attained a lower maximum speed (42 mph) on the snow of the ice cap than its rated maximum of 60 mph over water at sea level. Whether or not this was due to snow drag is far from clear, however; it may have been caused solely by differences in engine operation at the 6180 ft. altitude of Camp Century. If such drag does exist, it might also occur with the low ridges which appear on old floes of ice, presumably from the weathering of old hummocks or as the result of differential melting in the summer.

Larger-scale irregularities in the surface might combine with the basic design of the power units and fan of air-cushion vehicles to reduce its utility in the Arctic to a great extent. These vehicles are basically designed for economical operation over water; for such use, given a desirable maximum hover at height, the amount of air which escapes around the bottom of the skirt can be estimated. The size of the power plant and fan are determined by this. It is clear that if, instead of water, we had a flat surface with a sufficiently large crack - or ditch - in it, the machine could not hover over it indefinitely but would become grounded. In our application, this means that air-cushion vehicles designed for over-water purposes might not have sufficient hovering capacity to go slowly over rough surfaces, such as ice ridges. We might be in the unhappy position of having to move at top speed, so as not to become stuck, in just the regions we most would like to inch our way along. Here again the seriousness of this effect in practice is unknown; some indication of it may be found in the fact that the "Carabao" had a certain tendency to settle down on sastrugi when travelling slowly on the trail between Camp Tuto and Camp Century in Greenland. On one occasion it did "ground out" and, as would be expected when this phenomenon occurs, was only freed by a quite considerable effort.[1]

With this, though, as with the other problems we have mentioned, the magnitude of the difficulty - indeed sometimes its very presence - can only be determined by more or less extensive field trials. Only after such trials could we tell what changes in design need be made and what effect this would have on the economics of air-cushion vehicle operation in the North.

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1. G. Abele, private communication.

III

As we have observed earlier, one of the great advantages of air-cushion vehicles is their ability to operate indifferently over many types of surface - as long, in fact, as they are sufficiently flat. These craft are not designed for operation in terrain with strong local relief; as is well known, not even the ice in the Arctic presents a smooth flat surface. Here we shall try to see how high obstructions one might expect on the routes we have chosen to study; this is obviously of great importance in assessing the practicability of using an air-cushion vehicle over them.

The more complicated part of this question is the determination of the surface irregularities to be expected over ice. Except for snowdrifts, overland crossings do not change from season to season or from year to year; if a suitable route can be found it can be used indefinitely

In Canada, however, water routes change from one season to the next, due to the presence of ice in the winter months. In the regions we are studying in summer we can expect anything from open water, in the south, through mixtures of ice and water to ice many years old among the northwestern islands. In the winter there is an almost continuous ice cover, frequently of several years accumulation and many feet thick.

If this were the whole story there would be no problem. In general, however, the surface of this ice is far from flat. The continuous ice cover on the sea is broken up into floes of varying size; these are separated by stretches of "pressure ice", which may take the form of ridges, rafting, or hummocks. On rivers, long stretches of rough ice may occur at constricted points. At the very least these are serious impediments to the passage of any vehicle. They cause major concern over the suitability of air-cushion vehicles for arctic travel.

It is obviously crucial to have some idea of the height and frequency of these irregularities. Unfortunately, we soon find that pressure ridges vary from place to place; in the Baltic, for example, they are generally quite small - two to three feet high - and are separated by large flat floes, while ridges twenty to twenty-five feet high have been observed in the open sea in the Arctic Ocean. (Peschanskiy, 1963: 143). On the coasts of the arctic seas we have reports of ridges forty to sixty feet high, and on the Thelon River there are said to be patches of rough ice ten to fifteen feet high. These figures are sufficiently disturbing that we should spend some time in trying to learn just what we can expect.

Such an inquiry might profitably proceed in one of several ways. For example, there are many sledging journals with descriptions of travelling across sea ice; one could hope to find a large body of observations in them. Second, some sort of theoretical treatment should be possible to give us an idea of the number and height of ridges to be found under certain conditions. Third, the vast amount of scientific observations accumulated since World War II should produced something of value.

All of these, it turns out, can only furnish fragments of the picture; many of them are frequently disappointing. By a combination of all that is available, however, we can form some idea of the conditions actually present.

It is probably most profitable, first of all, to give a general qualitative outline of the growth on the ice cover of the sea, in particular that on the channels among the islands. In this no attempt will be made to give a detailed mathematical treatment of the process - this would be a complex undertaking even with a highly simplified model - but we shall attempt to outline the forces which affect the ice and thus try to gain some understanding of the nature of the ice surface in different areas at different times of the year.

As a start, let us imagine that we have a large expanse of ice-free water somewhere in an arctic environment; furthermore, let us assume for the moment that there are no currents, waves, nor wind. In the fall, the surface of this body of water will freeze into a smooth sheet; this layer of ice will steadily thicken during the winter[1] with the addition, in due course, of a cover of snow.

1. The ice thickness increases approximately as the square root of the total number of freezing degree-days. Various empirical formulas have been used to express this dependence. Peschanskiy (1963: 129) sets forth six different ones.

In confined areas, such as narrow bays, we see an approximation to these conditions; there in fact we find regions of flat ice which persist throughout the winter. As soon as these are thick enough to furnish adequate support[1] they obviously offer few problems to the operation of almost any sort of surface vehicle.

Such ideal conditions do not occur in general. In reality, we have waves, currents, and wind. It can easily be shown (Assur, 1963: 335ff; Peschanskiy, 1963: 138ff) that when ice becomes sufficiently thick and rigid, wave action of the most modest variety can cause a floe to fracture. For example, in a floe 100 yds. long and 6 ft. thick, a wave 2 in. high can cause a stress of the order of 115 psi. The flexural strength of sea ice is, typically, in the range of 40 to 70 psi (Brown, 1963: 95); we thus see how easily fracture can take place.

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1. The amount of time this takes can be seen from the following examples. The average of five years' data from Resolute for the time from freeze-up until the ice is 2 ft. thick is 38 days; after 68 more days it is 4 ft. thick. Three years' data for Cambridge Bay give 46 and 65 days, respectively, for the same quantities (Canada. Department of Transport. Meteorological Branch, 1961).

Even without waves we should not expect large fields of ice to remain smooth very long. Gales are quite frequent in the Arctic; there is always some frictional force between the ice surface and the air, no matter how smooth the former is; this is the same as saying that the wind causes a force in the plane of the ice surface. With a high enough wind, even small floes of smooth ice would be crushed, though, as we should expect, this requires wind speeds considerably above what have been observed[1].

In a large floe, however, as we can easily see, the compressive force caused by the wind increases as we go across the floe from the windward to the leeward side. This is the familiar problem of compressive forces in a thin plate; when the force becomes high enough--when the product of the wind speed and the length of the floe is large enough--the plate, or ice cover, will rupture. (Timoshenko and Gere, 1961: 319-439).

In any case, the sheet of ice is broken up. In theory this need not change the picture much, as long as conditions remain uniform: the floes are all of the same thickness, no irregularities have appeared to catch the wind or currents, and the velocity of the wind (and of the current) is the same everywhere in the region under consideration. In practice, clearly, such idealized conditions cannot be found. Then winds and currents tend to accelerate different floes by different amounts. We therefore find forces acting between the floes; with thin ones, these may cause adjacent edges to ride one over the other, or to

1. Peschanskiy (1963: 145) estimates that wind velocities of 60 mph are inadequate to break up a floe of weakly hummocked ice 3 ft. wide.

"raft"; with thicker ice, if the floes meet off center, chunks may be broken off. These chunks may be further crushed or carried to the upper or lower surface of the ice. Thus a pressure ridge is gradually formed.

Refreezing may again cause the formation of a single monolithic structure, which, later, will be subjected to the same forces; alternatively, new cracks may form across a floe, presumably as a result of shearing forces which arise from a lack of an equilibrium distribution of the ice fragments between the top and the bottom of the ice. Again, the edge of a floe may yield and crack simply due to an excess of weight on top of the ice. (Assur, 1963: 335ff). All these increase the surface roughness of the ice.

As the winter proceeds, changes in the direction of the wind, while compressing the ice and causing the formation of more pressure ridges in one area, can open up cracks and form leads in others. These leads may later freeze, causing ice of different ages and thickness to occur in the same region.

By late spring, when the ice is at its thickest for the year, these processes have, presumably, caused the greatest degree of roughness. In the summer there is, at the very least, a general softening of the relief. In Hudson Bay and, to a great extent, the channel along the northern coast of the continent, the ice breaks up and melts away altogether. Before this happens there is a period of "puddling", or of formation of pools of water on the ice. In themselves, these should not impede the passage of an air-cushion vehicle; eventually, however, they melt through the ice and drain away, leaving a honeycomb-like structure which, though shortlived, might be a nuisance to traverse.

Farther north, there are large areas in which the ice does not completely melt away. The warm weather, however, does cause the surface relief to become less angular; pressure ridges and hummocks settle and melt down until they are, on the average, one-half to one-third the winter average height. (Yakovlev, 1956: 6; 1960: 65)[1]. Irregular melting of the surface may cause low hills and valleys; these are both low and well-rounded and should give no trouble to an air-cushion vehicle.

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1. Particular hummocks may, of course, be quite high, even after several years weathering; thus Somov (1956) tells of hummocks which, when observed in 1954, were still the 7 m. high they were when they formed three years earlier.

In succeeding years pieces of this ice may be frozen into newly formed ice. They then form regions of different thickness which lead to more rapid formation of pressure ridges; from the point of view of travel they are also a help, for they provide fairly smooth surfaces for a vehicle to go over.

Although the various mechanical problems which arise in the study of ice formation can all be described mathematically, it is clear that there would be great difficulty in forming a complete enough picture even to derive rudimentary relations for ridge height. We might be able to construct a model of a simple enclosed region-- perhaps the Gulf of Boothia--but this would be of doubtful bearing on the present study. Nonetheless, the above description is sufficient for us to draw some general conclusions.

The prevailing winds over the arctic archipelago are from the Northwest. (Rae, 1951: 32). Furthermore, the Arctic Ocean, with its permanent cover of thick, rough ice, lies to the northwest of the islands. We can therefore describe two types of places in the archipelago where we would expect heavy, rough ice: in channels, such as M'Clure Strait or Prince Gustav Adolf Sea, which run to the southeast from the Arctic Ocean; we also look for bad ice conditions, perhaps to a lesser extent, at the southern end of long channels like McClintock Channel or the Gulf of Boothia, where the ice has little or no means of egress.

On the other hand, the channel along the northern continental coast lies "in the lee" of Banks, Victoria, and King William Islands. It runs east and west and, except at its western end, there is no direct means for the polar pack to enter. In short, all conditions seem to be met for it to have relatively smooth ice.

The other place we are curious about, the west coast of Hudson Bay, shows something quite different. Here again the prevailing winds are from the north and northwest. As a result the ice is, more often than not, forced away from the shore; other things being equal, we should expect a band of open water or of relatively smooth ice in this area[1].

Finally, we can note the conditions on a windward shore. As is quite clear, in an open channel there are only the differences of the forces arising from the momenta of the various floes to create ridges and hummocks; at the coast, however, we can observe the full impact of the forces themselves. Thus we should expect to find the highest ridges there. The same type of phenomenon - though caused by currents rather than primarily by the wind - can explain the rough ice on rivers, for example at Point Separation on the Mackenzie.

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1. N.N. Zubov (1964: 396) discusses an analogous situation off the New Siberian Islands. He states that the movement of the ice off shore causes a surface current which, in turn, causes the "welling up" of warmer water from lower levels, thus tending to perpetuate the shore lead. The same effect presumably occurs here.

All these, of course, are only the most qualitative and general observations, with almost all complicating details stripped away. Still, this picture seems in quite fair agreement with what is observed; for this reason such a long digression has probably been worth while.

The worst fault in all this is that it give us no idea of the height of the irregularities in the ice; it only serves to point up how intractable the general problem is. Although it should be possible, at least for simple situations, to derive a relation between the maximum ridge height expected and the thickness of the ice, we have not attempted to do so in the present work. We shall content ourselves here with the remark that, as we shall see below, such a limit does seem to exist. This is in keeping with the observations of the Russians, who find the average height of ridges and hummocks to be, on the average, comparable with the thickness of the ice. (Kirillov, 1957: 53).

Let us therefore turn to descriptions of the ice surface. The records of the many explorers who made sledging trips in the Canadian Arctic are rather disappointing for this purpose; they found hummocks and pressure ridges such ubiquitous phenomena that, except in cases of extraordinary roughness, they did not bother to comment on the detailed nature of the surface. The largest body of relevant material is in the records of the Franklin Search Expeditions (Great Britain, 1854-1855); only casual references are to be found in later explorers' journals[1].

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1. Such men tend, in general, only to give extreme examples of the pressure ridges to be found along the coasts of the Arctic Ocean.

Thus Stefansson (1921: 514) mentions a pressure ridge at Cape Isachsen which was measured to be 78 ft. high: Sverdrup (1904, Vo.l. I: 375) tells of one on the west coast of Axel Heiberg Island which he and Isachsen estimated to be over 80 ft. high. These are far from any of the routes discussed in the present report and need not concern us further.

Since the Franklin Search parties of concern here travelled on Melville Sound, M'Clure Strait, and the adjacent channels, the regions about which we can learn the most are those which seem to be of the least present-day potential for air-cushion vehicles. Nonetheless, these regions probably have the roughest ice conditions of those we are studying, and therefore a few quotations may profitably be given to show what bad travelling conditions might be like.

We have the following comments on Penny Strait by Lyall and Osborn:

> "The floe passed over today has been chiefly old ice, with here and there a few hummocks where there has been a crack followed by pressure." (Great Britain, 1854-1855: 174)

> "After crossing one heavy tier of hummocks, we reached comparatively level ice, with only occasional ridges of snow and piles of broken ice running across our path in a north and south direction.
>
> "We are at the eastern side of a belt of frozen pack, the extent of which we cannot see; but anything more extraordinary than the tumultuous scene before us I have never witnessed. To find any path through it by reeving was out of the question; and Captain Richards and myself had to climb over the masses on our hands and knees, and a dozen men with pickaxes and shovels fairly cut a causeway through the fragments... (Great Britain, 1854-1855: 126).

We have the following description of ice of different ages in M'Clure Strait, by G. F. Mecham:

> "On 19th May we cleared the Strait and travelled direct for Cape Providence. The ice, for ten miles off Cape Russell, we found of last year's formation, without a crack. After crossing

a barr ier of very old hummocks came to a lead over old floe, over which we travelled fifteen miles, and then entered heavy hummocks of young ice; through these we travelled thirty miles, and on the 23rd cleared them, about seven miles S. E. of Cape Providence." (Great Britain, 1854-1855: 89)

Next we have an example by F. J. Krabbe, of the effects of the weathering we discussed above; the locale is the southern side of M'Clure Strait:

"Passing mostly amongst very old floes, the angular parts of the hummocks being entirely gone, and with the protuberances caused by the annual rising of the floe; being large glassy mounds from 2 to 10 feet high, having somewhat the appearance (on a gigantic scale) of the old "Bull's-eye" as it formerly lay in decks, with the convex side upwards. Exclusive of these there were undulations in the floe level of 4 to 5 feet." (Great Britain, 1854-1855: 710)

As we have remarked earlier, snow should be a minor problem for air-cushion vehicles. We must, nonetheless, remember that drifts tend to form in the Arctic, even though the total amount of snowfall may be low. Thus, although McClintock, in crossing Fitzwilliam Strait, came on conditions which would seem ideal for a hovercraft - at least from the point of view of terrain:

"The weather gets worse, snow almost entirely covers the ice, here and there the top of a hummock appears; in the chance spot selected for our cooking pit, it is three feet deep. (Great Britain, 1854-1855: 567).

Sherard Osborn ran into drifts in Penney Strait which might well be an effective barrier for our vehicles:

> "We found the route we had cut through the pack, much encumbered by heavy snow drifts running across it, varying from 10 to 20 feet in height." (Great Britain, 1854-1855: 190).

We cannot conclude anything definite from these journals. Probably the fairest thing to say is that, although the very fact that the men were able to drag sledges long distances shows that the surface could not have been too rough in general, there frequently were difficult stretches for the sledges; these would probably have been difficult for an air-cushion vehicle too.

Unfortunately, suitable observations of the ice farther south are almost completely lacking. The few references in the literature relate mainly to Victoria Strait. The ice there is found to be rough - as we should expect from our earlier discussion and the fact that this strait provides an outlet of sorts to McClintock Channel. More to the point, it does not lie on any route of interest to us.

There is a certain amount of local knowledge available on the places we do care about. One source[1] says that the ice south of King William Island and over the route west to Cambridge Bay is, for the most part, quite flat. The average ridge height seems about two feet, while the highest ridges seen are four to six feet high. With a dog team, it is always possible to find a comparatively level route; this, of course, would not necessarily be true for a larger vehicle like a hovercraft.

1. Fr. P. Henry, o.m.i., Chesterfield Inlet, N.W.T., private communication.

Table II

Percentage Frequency of "Off-Shore" and "On-Shore" Winds on the West Coast of Hudson Bay During the Winter Months

Station and Wind Direction	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May
Coral Harbour								
"Off-shore" (NW, N, NE)	62	69	74	76	69	65	63	58
East	14	15	15	8	12	18	14	15
"On-shore" (SE, S, SW)	14	8	4	3	4	5	8	12
West	8	5	3	6	5	3	7	9
Calm	2	3	4	7	10	9	8	6
Chesterfield								
"Off-shore" (W, NW, N)	55	62	69	80	76	65	61	52
Northeast	12	10	9	5	5	7	10	14
"On-shore" (E, SE, S)	27	22	17	10	12	21	23	28
Southwest	5	4	3	2	2	3	3	4
Calm	1	2	2	3	5	4	3	2
Churchill								
"Off-shore" (W, NW, N)	57	58	70	80	68	60	54	48
Northeast	5	6	4	2	5	6	7	16
"On-shore" (E, SE, S)	26	27	17	9	20	26	32	32
Southwest	11	7	8	7	6	6	6	3
Calm	1	2	1	2	1	2	1	1

There is general agreement that open water or a strip of smooth ice is often found along the coast of Hudson Bay to the north (and, farther, northeast) of Churchill. We have already pointed out that this is connected with the prevailing winds being off-shore. The proportion of the time that water or smooth ice is present is unknown; it must be related, in some manner, to the frequency of these off-shore winds. Table II (Canada, Department of Transport, Meteorological Branch, 1959) gives a summary of observations from stations along this coast and, presumably, shows roughly the amount of time we should expect to find this particular smooth way.

About the Mackenzie River -probably the most attractive place to start trying out the northern capabilites of air-cushion vehicles - we have the least amount of reliable information. What there is indicates that a vehicle with a four foot clearance should be able to go along the Mackenzie in winter. The roughest parts are said to be near Norman Wells, and at Point Separation; at the latter, in particular, some winters see the formation of rough ice over a distance of several miles and to a height that is variously estimated at 20 to 30 feet.

In general, though, due to the width of the river, the hummocks are said to be two to three feet high. The ice in the shallows along the sides of the river is supposed to be smoother; because of this, we believe that an air-cushion vehicle could get by even the rough stretches described above. In some parts there may be banks suitable for use if everything else proved too rough[1]. In brief, there is almost nothing solid to form an opinion on.

1. Along great parts of the river, however, there are "out banks" 30 or so feet high (Taylor, 1947: 59ff).

but the indications are that these craft could find a suitable wintertime route on the Mackenzie.

This exhausts our second class of material; we are left with the third; recent "scientific" observations. Under this heading we have three bodies of data which might be of use in the present study: aerial photographs, the reports of the aerial ice observing and reconnaisance program of the Meteorological Branch, Department of Transport, and sundry manuscript reports of the Marine Sciences Department, U.S. Naval Oceanographic Office. As the following discussion shows, none of these is satisfactory for our purposes. Nonetheless, taken together they put some details into what is still essentially a qualitative picture.

The most general are the reports issued since 1957 by the Meteorological Branch. These are the reports of ice surveying flights; they contain maps of the distribution, age, and surface characteristics of the ice seen along different routes. Although, apart from the more usual "shipping routes", such as Baffin Bay and Lancaster Sound in the north and the Beaufort Sea - Coronation Gulf - Simpson Strait route in the west, coverage is apt to be sketchy, this material is extremely useful.

These observations cover half the year -from April to October. Before we can extract concise information from them, we must decide what seasons of the year we are interested in. So far we have tacitly assumed that the worst conditions for air-cushion vehicle operation are at the end of winter, when the ice is at its roughest. This seems sensible. Over two of our three routes, it is true, ice virtually completely disappears

Table III

Summary of Late Winter Ice Conditions

I. Resolute - Mould Bay (approx. 525 Miles)

1961 (average of two flights):

Resolute - Cape Hay, Melville Id. (approx. 330 mi.): 75% winter Ice, 25% polar ice.

1962 (average of three flights):

Resolute - Cape Hay: 85% thick winter ice, 3/10 ridging; 15% young polar ice.
Cape James Ross, Melville Id. - Mould Bay (150 mi): 60 % thick winter ice, 2/10 ridging; 40% young polar ice, 3/10 hummocking.

1963: Resolute - Cape Hay: 85% thick winter ice, 1 to 2/10 ridging; 15% young polar ice, 2/10 hummocking.
Cape Hay - Cape Russell, Melville Id. (approx, 110 mi.): 60% thick winter ice, 3/10 ridging; 40% young polar ice, 2/10 hummocking.
Cape Russell - Mould Bay (approx. 80 mi.): thick winter ice.

II. Chantrey Inlet - Coppermine (approx. 575 miles)

1958 (average of two flights):

Grant Pt. - Sturt Pt. (Victoria Id.) (approx. 115 mi.): 75% winter ice, 25% polar ice, light ridging.
Remainder: winter ice, light ridging.

1959: Entire Route: winter ice, light to moderate ridging.

1960: Approx. 40 miles to East of Jenny Lind Id.: 80% thick winter ice; 20% polar ice, light hummocking.
Remainder: thick winter ice, light ridging.

1961 (average of two flights): Entire route: thick winter ice, ridging reported heavy in April, light in May.

1962: Grant Pt. - Jenny Lind Id. (approx. 75 mi.): 90% thick winter, 2 to 3/10 ridging; 10% young polar ice, 5/10 hummocking.
Remainder: thick winter ice, average of 2/10 ridging.

each summer, and some thought must be given to what we might expect in the transition period. There is little satisfactory data about break-up on the Mackenzie. On the part of Hudson Bay we are considering traversing and along the north coast of the continent (as well as on a large part of the route from Resolute to Mould Bay) we do have two special problems at break-up: the rotten ice mentioned above and, what is probably more serious, the "steps", possibly up to 4 ft. high that the craft must climb to get onto a floe from the water. (Dickenson, 1964: 12) Not only are these transitory phenomena but, as we shall see, they are probably not as serious as the pressure ridges and hummocks which we have, month after month, in the winter. For this reason we give, in Table III (Canada, Department of Transport. Meteorological Branch, 1960 - 1963; 1962 - 1963; 1963 - 1964), summaries of the late winter ice conditions, as described in these reports, for our two routes north of the continent. There is not satisfactory coverage for the Hudson Bay section.

These observations confirm what we have already stated. In Melville Sound and M'Clure Strait, there is a considerable proportion of "polar" ice - ice more than one season old - and hummocks and pressure ridges cover a good fraction of the surface. From Chantrey Inlet to Coppermine, on the other hand, ice is mainly of a single year's growth. The exception is the region from the west end of Simpson Strait to a line west of Jenny Lind Island (actually passing about through Sturt Point on

Victoria Island). Here, in some years, there is a small quantity of old ice - the same ice as that which comes from McClintock Channel and, we have seen, makes Victoria Strait so rough. Again as we would expect, this route has considerably less surface roughness than the more northern one.

These reports characterize surface features by the proportion of the ice they cover; we have, therefore, the problem of correlating such a description with the quantities we are concerned with in air-cushion vehicle operation: how many obstructions per mile and how high. At first glance, the series of reports of the U. S. Naval Oceanographic Office Project BIRDS EYE (U. S. Naval Oceanographic Office, Marine Sciences Department 1964 - 1965), should help in doing this. These reports are summaries of ice observing flights; they list the ice type and extent of surface features seen, at ten-minute intervals, throughout the flight; they also give "ridge counts", or the number of ridges which cross a fixed line of sight from the aircraft in a given distance. They do not, as yet, give estimates of ridge height beyond stating whether they are large or small.

Unfortunately, these flights are solely over the arctic basin itself. Here the ice is predominately the so-called "arctic pack", which seldom invades the regions we are studying in any amount. Only in M'Clure Strait would we ever meet conditions similar to the ones described in these reports.

Table IV

Average Ridge Counts in the Arctic Ocean

Fraction of surface covered by ridges	Average number of ridges per mile	Minimum	Maximum	Number of Observations
	Small Ridges			
1/10	14.6	3.5	39.7	17
2/10	13.5 ± 5.3 (s.d.)	2.9	24.3	32
3/10	12.7	4.1	20.8	27
4/10	10.8	3.6	14.8	6
	Large Ridges			
1/10	7.5	3.7	9.0	6
2/10	11.4 ± 6.6 (s.d.)	3.3	32.7	50
3/10	15.3	3.2	43.0	157
4/10	16.1	4.2	34.0	72
5/10	15.9	5.8	29.8	40
6/10	13.0	10.6	20.4	9

The pressure ridges in the Arctic Ocean are much larger than what we would normally expect to meet. This has immediate bearing on the utility of the Project BIRDS EYE ridge counts to us, for high pressure ridges have wider bases than low ones, and accordingly the same number of large ridges would cover a larger fraction of the ice, and bias the correlation we are trying to make.

Nonetheless, it is of some interest to study a limited amount of this information and see what it offers. Accordingly we present, in Table IV, averages of the ridge counts for different fractions of the surface being covered by ridges. The observations have been separated into those which record "large ridges" and those of "small ridges", but no effort has been made here to differentiate between ice of varying degrees of development.

As can be seen by the size of the sample standard deviations given, the range of ridge counts in any one category is so great that we cannot hope to learn anything very definite. With the "large ridges" we do see a general increase in the number of ridges as the total proportion of the ice covered increases. This is quite what we would expect. We should also expect the number of separate ridges counted to level off when the total amount of surface area covered became so large that the ridges start to overlap; this too we may imagine appears in the present results. The behaviour of the "small ridge" counts, though, show that we cannot really make any sure statements from these data.

Neither of these sources of information tells us about the height of the ridges. Various direct ways of measuring ridge heights can easily be imagined -- for example, making a traverse on the surface or using a high resolution laser altimeter. Nothing of this sort seems to have been tried out in more than a very limited way [1].

Another possibility is the use of aerial photographs, on which heights can be measured by parralactic or other methods. Here we can easily show that, if we wish to measure heights to the nearest foot or two (the amount of accuracy we must have for the present purpose), we must have photographs taken at a comparatively low level [2]. We thus end up looking for photographs of the channels in the arctic archipelago taken in winter at elevations of six thousand feet or less. As one would expect, such material is not common.

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1. As referred to above, the Russians have surveyed the relief of the ice floes they winter on. (Yakovlev, 1956).

2. If we work with a stereoscopic pair of photographs, the measured parallax (p) is related to the height of the surface feature (h), the height of the camera (H), and the distance between the principal points of the pair of pictures, D, by the Proportion:

$$p/D = h/H$$

Thus, if we take a minimum usable parallax of 0.001 in, and wish to measure features 1 ft. high on photgraphs with, as a typical example, 4 in. spacing between principal points, we see that the maximum altitude at which we can take the photographs is 4000 ft.

There are, however, two series of photographs available. One[1] covers 45 miles of flight path off the northwest shores of Prince Patrick and Borden Island: the other[2] furnishes isolated pictures of the ice on Hudson Bay.

Here we again have situation that the available material does not have direct bearing on the areas in which are interested. The pictures of the ice in the Arctic Ocean, however, are not of the arctic pack alone, but cover a variety of ice types. We can hope that conditions west of Resolute might be somewhat similar; if anything, we should expect the ice in Melville Sound and M'Clure Strait to be somewhat less rough than that of these photographs. The flight over Hudson Bay was from Moosonee to Cape Churchill and then to Mansell island. It does not show us ice conditions alons the shore but it does give a general idea of conditions in the more southern regions.

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1. RCAF designation RR2415 "Bold Survey".

2. RCAF designation RR 22 "Ice Recce".

These photographs emphasize a point we have already made: hummocking and ridging are in no way uniform phenomena, either in distribution or in shape. We frequently see isolated humps; ridges can be two feet high in one place and eight in another. This must be considered in making any sensible quantitative measure of ridge heights as they affect surface operations. Air-cushion vehicles are maneuverable; if we come to a field of rough ice, we can do one of two things. If we are sure that all the ridges and hummocks are lower than the vehicle clearance, we would go across them on as straight a course as possible. If we are not so confident, we would go around as many of the isolated pinnacles and humps as we can and try to cross ridges at their lowest parts.

For this reason we cannot proceed in a mechanical manner if we want a fair picture of the surface roughness. Simple methods, such as laying a straight edge on a detailed contour map or studying the profile of a straight course over the ice give results that are weighted too heavily with obstructions which are high but of limited lateral extent. Admittedly, deciding from a photograph which of these one could go around in reality is subjective, but not much more so than the decisions of the driver. Accordingly, we drew five parallel lines one inch apart on the photographs.

These represented possible ideal "flight paths"; since one inch corresponds to 225 to 300 yards on the ice, they should be far enough apart to make an averaging process sensible. These lines were changed to avoid obstacles which it seemed clear a man on the ground would go around, and the height of the ridges and hummocks lying across these new lines was measured.

Since, by good fortune, almost all the suitable pictures were taken in bright sunlight, the height of a ridge was found from the length of the shadow it cast and the altitude of the sun as calculated for the particular date, time, and place. This method, of course, is liable to several sorts of errors. The ridge may run roughly parallel to the sun's rays and not cast a usable shadow. The angle of view of the camera is so great that shadows at the edges of pictures can appear considerably longer or shorter than they are. In the worst case among the photographs used in this study, this effect can amount to a 33% error for ridges at the very edge of the field of view. Due to the availability of stereoscopic views, only the central portion of each picture was used, which should lead to errors no larger than about 15% from this source.

The great advantages of this method are that it is quick, so that more data can be obtained than by other means, and, at least for the author, it is much more objective than the various methods using measurements of the parallax between stereoscopic pairs of photographs. Furthermore, the shadow lengths on the pictures used are such that there is an uncertainty of a foot or so in the deduced ridge heights - or 33% of the height of a three foot ridge and 17% of a six foot one. This uncertainty, which is, by the way, about the same as that to be expected from good parallax measurements on the same photographs, makes it senseless to try for anything too elegant.

The results of these measurements, summarized to give the number of ridges in various ranges of height per mile, are given in Table V. For the pictures taken over the Arctic Ocean we give a further division according to the characterization of the ice given by an ice observer on the same flight (Canada. Department of Transport. Meteorological Branch, 1964:9)

Comparing this material with that in Table III, we see that on the route from Resolute to Mould Bay we would expect to find a considerable fraction of the ice with ridges and hummocks up to six or eight feet high. A vehicle with the 3ft. 6in. clearance of the SR.N5 could only go along such a route by picking its way very carefully through the route regions or else by making large detours. Nonetheless, it probably could make the trip, particularly if it were feasible to have an aircraft survey the route beforehand.

Farther south we should expect fewer difficulties. These photo-

Table V

Ridge Height Distribution

Ice Description and Distance Covered*	Ridges per mile per height interval				
Run I - Arctic Ocean	0 to 2'6"	2'6" to 4'9"	4'9" to 7'3"	7'3" to 9'6"	9'6" to 12'3"
8/10 medium winter, 2/10 young ice, 2/10 ridging. (9.18 mi.)	5.75	1.09			
6/10 young polar, 3/10 arctic pack, 1/10 thick winter, 7/10 ridging. (14.2 mi.)	3.73	1.89	.46	.1	.04
Run 2 - Arctic Ocean	0 to 2'6"	2'6" to 5'1"	5'1" to 7'8"	greater than 7'8"	
Thick winter. (4.15 mi.)	4.53	3.08	.86		
Young ice. (10.34 mi.)	5.46	.12			
8/10 medium winter, 2/10 thick winter, 4/10 ridging. (6.93mi.)	3.49	3.47	.77	.60	
Run 3 - Hudson Bay	0 to 1 ft	1 ft - 2 ft	2 ft - 3 ft		
11.31 miles	6.17	1.96	.28		

* These distances are those covered by the photographs. The actual track lengths scanned, as discussed in the text, are five times greater.

graphs indicate that the routes between Chantrey Inlet and Coppermine should not present too many problems to a craft like the SR.N5. We would, of course, meet ridges higher than 3 ft. 6 in. but they should be few in number and more easily circumvented.

In the entire sample we have for study, we see that there are few ridges more than 6 ft. high. In other words, the clearance of present air-cushion vehicles is marginal for arctic use. If ridge heights were the only problem in using air-cushion vehicles in the North, it seems that a craft with a ground clearance of 6 ft. or so (which, accordingly, would be somewhat larger) would be much more useful for general arctic use.

There are a few points which deserve mention before we leave this subject of ice roughness. First, we have not considered ridges along the shore in detail. As we have seen, these can be much higher than those in the open channels; they have been observed up to 60 ft. high even within the archipelago [1].

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1. The Franklin Search Parties (Great Britain, 1855: 131) found a ridge of this height on the coast of Bathurst Island in 1853; in May of 1830 J.C. Ross estimated the height of one on the northwest coast of King William Island to be 40 ft. (Ross, 1835: 418).

Such ridges, however, are a fairly special problem, since they would be encountered only at the ends of a journey. Here either a particular course could be marked through them, or if, necessary, a smooth way made over them. Second, we cannot forget the troubles air-cushion vehicles have with slow speed operation. Moving a pointer across an aerial photograph at a speed which is the equivalent of, say, 60 mph on the ground is obviously only the crudest way to judge the practicability of travelling at such a speed. Still, it is the only method presently available; such tests show that speeds of 60 mph would be reckless in going through regions of rough ice like those shown; a guess at a reasonable speed might be 20mph.

Finally, a point which is more one of general interest in forming a picture of the ice surface: there is not, at least in the available sample of pictures, a continuous spectrum of large and small ridges, as might be expected from the analogy of waves on the sea. In thin ice there are, of course, only small ridges and rafting; thicker ice has mainly larger ridges with only a few of the very small ones [1]. A possible explanation of this is that ice tends to fracture repeatedly at the same place; if, however, we assume the crack fills with water and is

1. We do not consider here the small-scale irregularities which cover the surface of older floes; presumably, they are due to weathering.

frozen, this does not seem to be in keeping with Assur's calculations (Assur, 1963: 339). Another explanation might be found in the relative infrequency of gales in comparison with the rate of increase of thickness of ice. At present, however, it is neither profitable nor practicable to pursue this question further.

To complete the discussion of terrain, we must turn to the overland part of our projected route from Churchill to Cambridge Bay and Coppermine: the route from Baker Lake or the head of Wager Bay to Chantrey Inlet or McLoughlin Bay. Much of this lies over country which might be described as the locus classicus of those who look on northern Canada as wide, gently rolling, treeless land. It would seem almost ideally suited to air-cushion vehicles.

These craft, however, might have trouble with the hillier country which must be crossed at the southern end of the land route. The conventional choice for this route and, at about 150 miles, the shortest land crossing, is that used by Brown (1936: 26), who went by tractor from Wager Bay to Chantrey Inlet in the winter of 1929. His description has several references to hills; for example, they

> "struck into some hilly country so bad in fact that the dog sled capsized several times on the steep slopes. Tractor, however, negotiated them with but little trouble." (Brown, 1936: 30)

He also remarks on the prevalence of snowdrifts in such country in winter. None of this sounds too propitious for air-cushion vehicles.

For these reasons a more southern route - heading west from Baker Lake, more or less along the Thelon River, and then going north from Aberdeen Lake - might be more suitable. Much of this lies on the route taken by Exercise Musk-Ox in 1946; a comment on it was that it was better than expected but there was "a certain amount of trouble with rocks" (Wilson 1947: 14). This overland crossing is about 100 miles longer than the more northern one, but, since Wager Bay is considerably to the east of Chesterfield Inlet, the overall distance from Churchill to points west of King William Island is almost the same by either route.

According to the studies made by the Department of Geography at McGill (1963) we should be able to lay out a route here which passed almost entirely over flat country. The southern section would again cause the most trouble, and it would be necessary to find a way around the narrowest parts of the Thelon River where, as we have noted, there is very rough ice indeed in winter. Next to this, boulders are probably the most serious problem. On the whole, though, there is every reason to believe that a suitable route could be laid out. As we have already said, one of the great advantages of such a route is that once laid out it would not change.

We may summarize this section as follows:

Of the three routes we have chosen to study, we can be cautiously optimistic that two of them - the Mackenzie River and the route from Churchill to Cambridge Bay and Coppermine - would prove practicable as year-round routes for existing air-cushion vehicles, at least from the point of view of finding a usable surface to travel over. The third route, from Resolute to Mould Bay, would be considerably more difficult. Here we should anticipate having to make wide detours at times, and the problem of finding a suitable route from surface observations alone might be troublesome. We must, however, remember that all this is based on inadequate data and local information and can only be regarded as tentative conclusions.

From the point of view of vehicle design, it appears that the present craft, with 3 ft. 6 in. or 4ft. clearance, are somewhat marginal for general operation over ice. We should expect much less difficulty with a vehicle with 6 ft. clearance. The clearance also affects the amount of time an air-cushion vehicle could use its normal cruising speed; as we have seen, existing vehicles would probably be forced to move quite slowly most of the time they were over rough ice.

IV

From our present point of view, the weather of the Canadian North is similar to the terrain and the ice. There are some elements which are virtually tailor-made for air-cushion vehicle operation and others which might seriously impede their use. For example, in summer the arctic archipelago is a region of prevalent low cloud (Rae., 1951: 24). This frequently causes trouble in operating aircraft; it should have little effect with air-cushion vehicles. Fog is a like matter. In principle, an air-cushion vehicle could move ahead in fog as the opportunity allowed; when the visibility became too poor it could settle down at almost any point and wait for the weather to clear.

On the other hand, long periods of persistent reduction in visibility would be a serious problem. Present-day air-cushion vehicles operate most efficiently at about 60 kts; at this speed we need, as a guess, one-half to one mile visibility to be able to avoid obstacles. Blowing snow can keep the visibility below this limit for days at a time. Similarly, high winds can prevent useful operation. Air-cushion vehicles have, it is true, shown a great ability to get moving under remarkably poor conditions[1], but they still have almost no resistance to sidewise forces. In a gusty cross wind it would be hard enough to keep on a fixed course; operation over difficult terrain might well be impossible.

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1. As, for example, in the demonstration given, in a full gale, off the Isle of Wight in September 1964 (Lambert, 1964 : 50a).

The weather of the Arctic has been excellently described in a number of places[1]; there is no need to do it again. The chief features that concern us here are the following:

1. The prevalence of low stratus over the islands in summer, together with comparatively frequent fog.

2. Winter gales with an attendant reduction in visibility from blowing snow.

3. Other phenomena which lead to impaired visibility. One of these is ice fog; another, the simultaneous occurrence of thick low stratus, low altitude of the sun, and a complete snow cover. This combination can produce a complete loss of perspective and sense of distance.

Let us take these up in turn:

1. Although low stratus is not a source of trouble for air-cushion vehicles, fog can be, since it limits horizontal visibility. In summer, the arctic archipelago is foggy, but no more so than much of the British columbia and Newfoundland coasts. Table VI[2] gives data on the frequency of fog at Resolute with comparative figures for points farther south.

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1. Examples are: Rae (1951); Canada. Hydrographic Service (1959, Vol. 1: 121ff); Dunbar, M. and K.R. Greenaway (1956: 450 ff).

2. Source: Meteorological Branch, Department of Transport of Canada. General Summaries of Hourly Weather Observations in Canada, Toronto and Ottawa. Various dates.

Table VI

Percentage Frequency of Fog at Selected Stations for the Summer Months

Station and Visibility	Apr.	May	June	July	Aug.	Sept.	Oct.
Resolute							
0 to 1/4 mi.		1.1	4.7	7.3	6.7	3.3	
3/8 to ½ mi.		.69	1.2	2.7	2.2	1.7	
5/8 to 6 mi.		3.0	5.2	5.9	8.3	5.9	
Cambridge Bay							
0 to 1/4 mi.		1.6	1.1	1.1	.84	1.4	1.0
3/8 to ½ mi.		1.1	1.2	.25	.55	.54	.50
5/8 to 6 mi.		7.2	6.5	3.3	5.2	6.1	4.8
Aklavik							
0 to 1/4 mi.	.21	.40	.07	.13	.54	.76	.20
3/8 to ½ mi.	.07	.67	.21	.20	.34	.68	.87
5/8 to 6 mi.	.42	.87	.90	1.01	2.0	2.3	1.1
Norman Wells							
0 to 1/4 mi.	.0	.10	.05	.10	.12	.46	.25
3/8 to ½mi.	.0	.12	.0	.0	.13	.16	.77
5/8 to 6 mi.	.0	.23	.24	.40	.74	1.4	2.1
Fort Simpson							
0 to 1/4 mi.	.03	.05	.16	.08	.52	.62	.94
3/8 to ½ mi.	.02	.07	.12	.05	.25	.28	.71
5/8 to 6 mi.	.10	.18	.57	.64	.69	1.4	2.9
Cape St. James, B. C.							
0 to 1/4 mi.	2.9	5.0	7.5	10.6	10.3	8.9	11.3
3/8 to ½ mi.	2.4	2.1	2.0	3.6	3.6	2.3	1.8
5/8 to 6 mi.	10.6	10.6	8.9	6.0	7.0	8.4	14.4
Twillingate, Nfld.							
0 to 1/4 mi.	2.1	3.2	4.3	1.8	1.02	.75	.60
3/8 to ½ mi.	1.4	2.3	1.3	.91	.54	.17	.99
5/8 to 6 mi.	17.2	16.7	13.9	9.3	8.2	6.1	13.6

Table based on eight year's data, except for Resolute (seven, and Aklavik and Cape St. James (both six).

It also summarizes observations from points along the Mackenzie River; these, being inland, have little fog.

It must be kept in mind that fogs tend to come in spells, with intervening periods which are not suitable for its formation. Furthermore, fog is not a persistently thick phenomenon, instead, there are times during which a surface vehicle could move along with no trouble followed by ones in which it would have to stop and wait. Such operation, though a nuisance, should be perfectly possible with an air-cushion vehicle.

In addition, the weather stations in the arctic archipelago are almost invariably on the coast - the place where fog is worst. As the Pilot of Arctic Canada points out (Canada. Hydrographic Service, 1959), fewer fogs are observed inland or out to sea than are on the coast. By planning a route with this in mind and by accepting the fact that one might have to sit out some of the foggiest periods, fogs in the Arctic - as those farther south - should not be an insuperable problem.

2. High winds. Rae (1951: 33) has remarked that the Arctic is not, in general, a particularly windy place; he attributes any feeling that it is to the lack of obstruction to break the wind's force. High winds do occur, especially in fall and winter. They can affect air-cushion

vehicle operation in two ways: the wind may be so strong that adequate steering is impossible, or, if there is snow on the ground, the wind may blow it along and so reduce visibility.

The first would not seem a particularly serious problem as long as the vehicle can keep moving at a good speed. Design cruising speeds for air-cushion vehicles are generally about 60mph; if we could travel at this speed, we should expect winds up to about 30 mph to be tolerable as far as maneuverability is concerned. Such a wind speed would mean that the craft's heading would never be more than 25° from the direction of travel; this should be tolerable. The most serious result of operating in such winds would probably be increased fuel consumption [1].

At least at the weather stations, such winds seem fairly infrequent [2]. As a rule of thumb, we can say that in the winter months we expect winds of 20 mph and above 30% of the time; those of 30 mph and above, about 10% of time (these figures do not apply to Alert and Isachsen, which have much calmer weather). Here the Pilot of Arctic Canada's comment (Canada. Hydrographic Service, 1959: 132) winds are apt to be considerably higher at sea.

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1. This increase in fuel consumption has two causes. The first is obvious, in a head-wind, the vehicle is slowed down. In addition, in a cross-wind, there can be a significant increase in the aero-dynamic drag - up to 30% or so. This also causes an increase in fuel consumption.

2. A convenient analysis of winds by speed is given in Fraser (1964).

Nonetheless, the effect of the wind in producing blowing snow is probably more important than the mere fact of its presence. With the low temperatures of the arctic winter, the snow is so dry and fine that almost any wind can carry it along. For any one place we can obtain a rough relation between wind speed and the reduction in visibility caused by blowing snow (Fraser, 1964); such a relation apparently varies not only from place to place but also from month to month. In addition, the length of time the wind has been blowing can influence the situation, for there are cases in which, after the wind has blown for several hours or days, the visibility suddenly improves although there is no let up in the wind.[1]

These two criteria - high winds and heavy blowing snow - can be combined to give a quantitative picture of the winter storms. For this, it is only sensible to use a simpler relation between wind speed and blowing snow than the rather complicated situation outlined above; we therefore adopt Rae's relation(Rae 1951: 30), derived from observations at Resolute, that winds of 20 to 25 mph in general reduce visibility to one mile or less; that is, to the limit we earlier assumed for high-speed operation of a surface vehicle.

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1. For example, at Alert the wind blew at between 30 and 55 mph for over 36 hrs. on 18 -19 April, 1958. For the first eighteen hours of this storm, the visibility was $\frac{1}{2}$ mi. or less due to blowing snow; it then cleared to 5mi or more for the rest of the storm. (Canada. Department of Transport. Meteorological Branch, 1958).

In Figures 2 - 7 we give examples of the frequency and length of stormy and clear periods in the Arctic in the winter months [1]. In these, "stormy weather" is that in which the visibility is stated to be one mile or less or the wind is 20mph or above. (This apparent duplication of criteria is used to eliminate spurious "clear weather" observations arising from a short lull in the wind or a momentary clearing of the snow [2].

These graphs show the protracted storms, sometimes lasting up to several days, which we expect. In between these, however, there are periods of clear, calm weather. These are often remarkably long - 75% of the "clear weather" observations at Mould Bay in January come in periods of 48 hours, or more - and would furnish ample time for air-cushion vehicles to make long journeys.

3. There are miscellaneous other situations in which it would be difficult to operate an air-cushion vehicle. One example is the type of whiteout which can occur with a complete cloud cover of low, thick stratus and a continuous snow cover on the surface. If the sun is

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1. Sources: Meteorological Branch, Department of Transport of Canada. Climatic Summaries for the Joint Arctic Weather Stations. Various dates; Arctic Summary, various dates.

2. We have also assumed that one observation of weather better than these limits between two in which it is worse does not create a period of weather suitable for operation; in other words, we only count periods of weather better than these limits and longer than six hours as suitable for air-cushion vehicle travel.

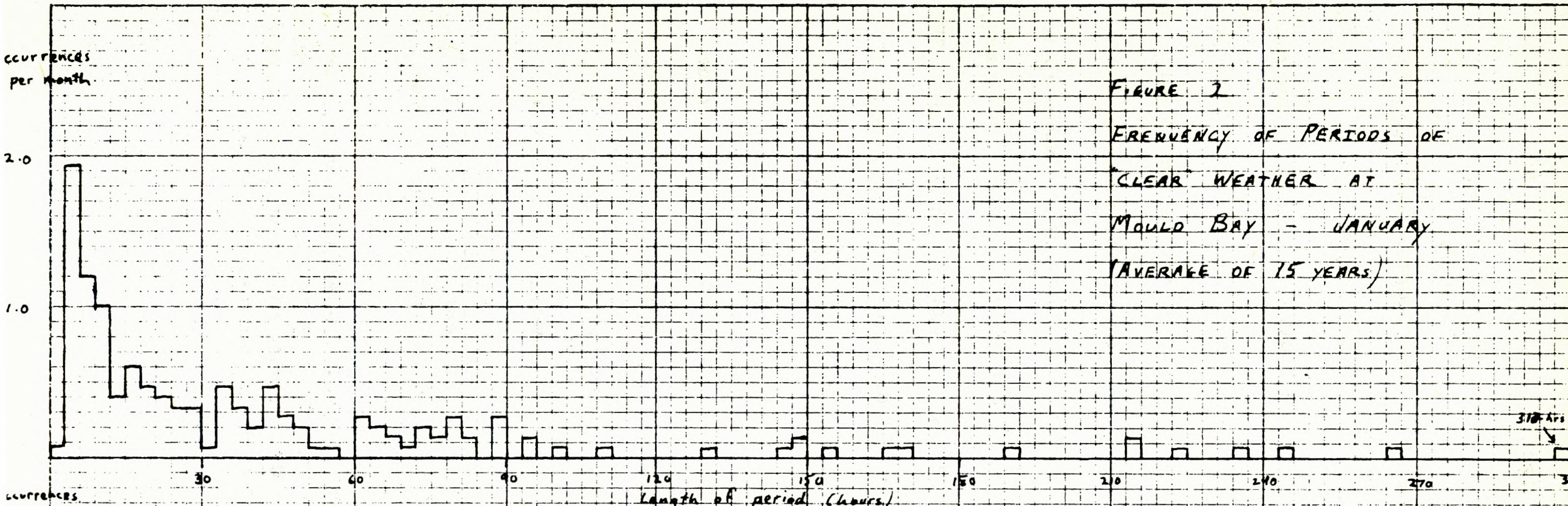

FIGURE 2
FREQUENCY OF PERIODS OF "CLEAR" WEATHER AT MOULD BAY - JANUARY (AVERAGE OF 15 YEARS)

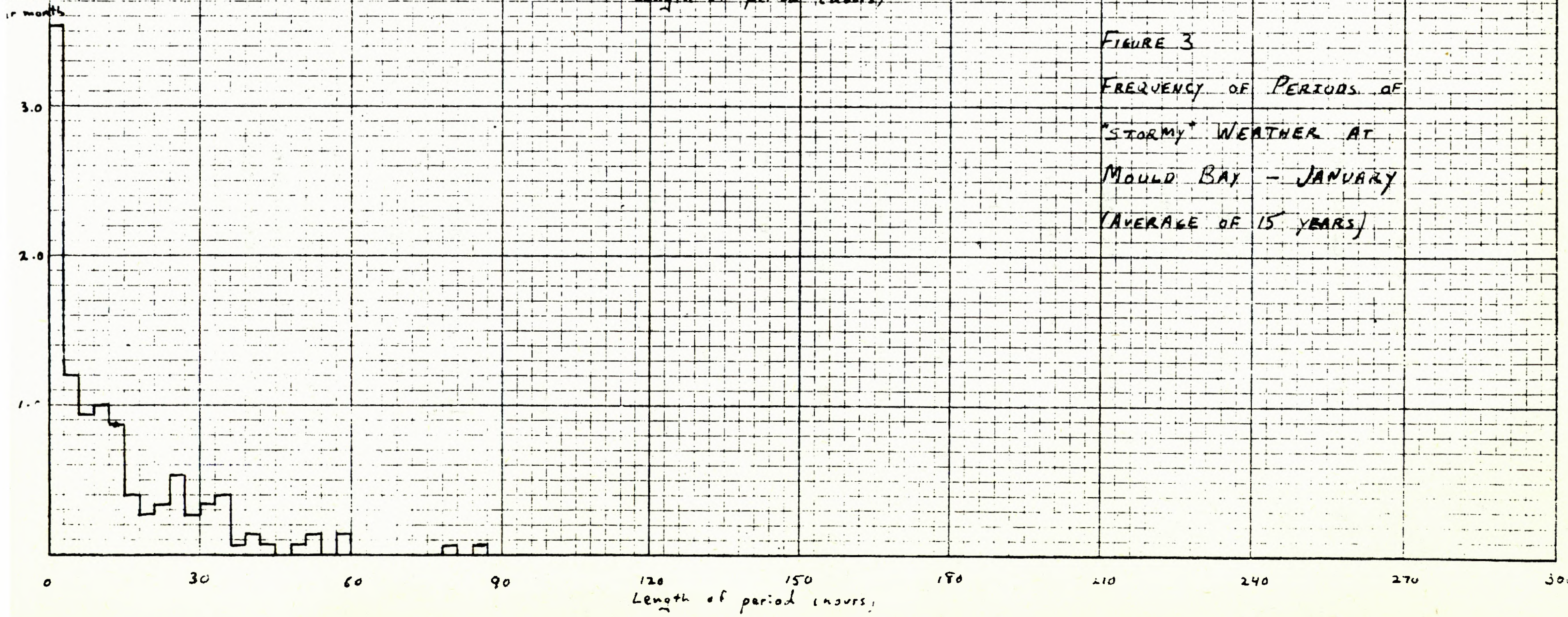

FIGURE 3
FREQUENCY OF PERIODS OF "STORMY" WEATHER AT MOULD BAY - JANUARY (AVERAGE OF 15 YEARS)

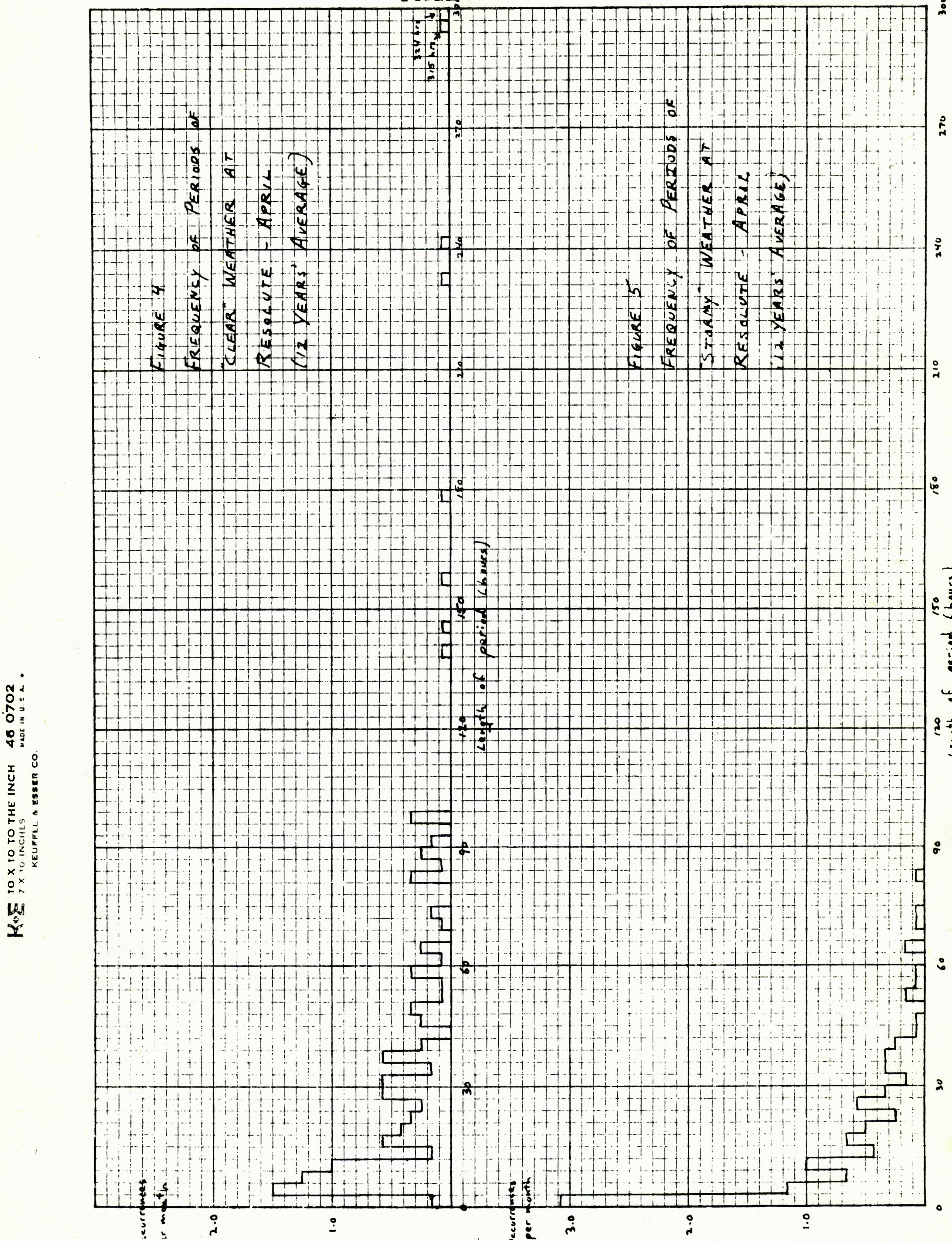
Figure 4
Frequency of Periods of
"Clear" Weather at
Resolute - April
(12 Years' Average)
Figure 5
Frequency of Periods of
"Stormy" Weather at
Resolute - April
(12 Years' Average)
Length of period (hours)
Occurrences per month
0
30
60
90
120
150
180
210
240
270
300
1.0
2.0
3.0

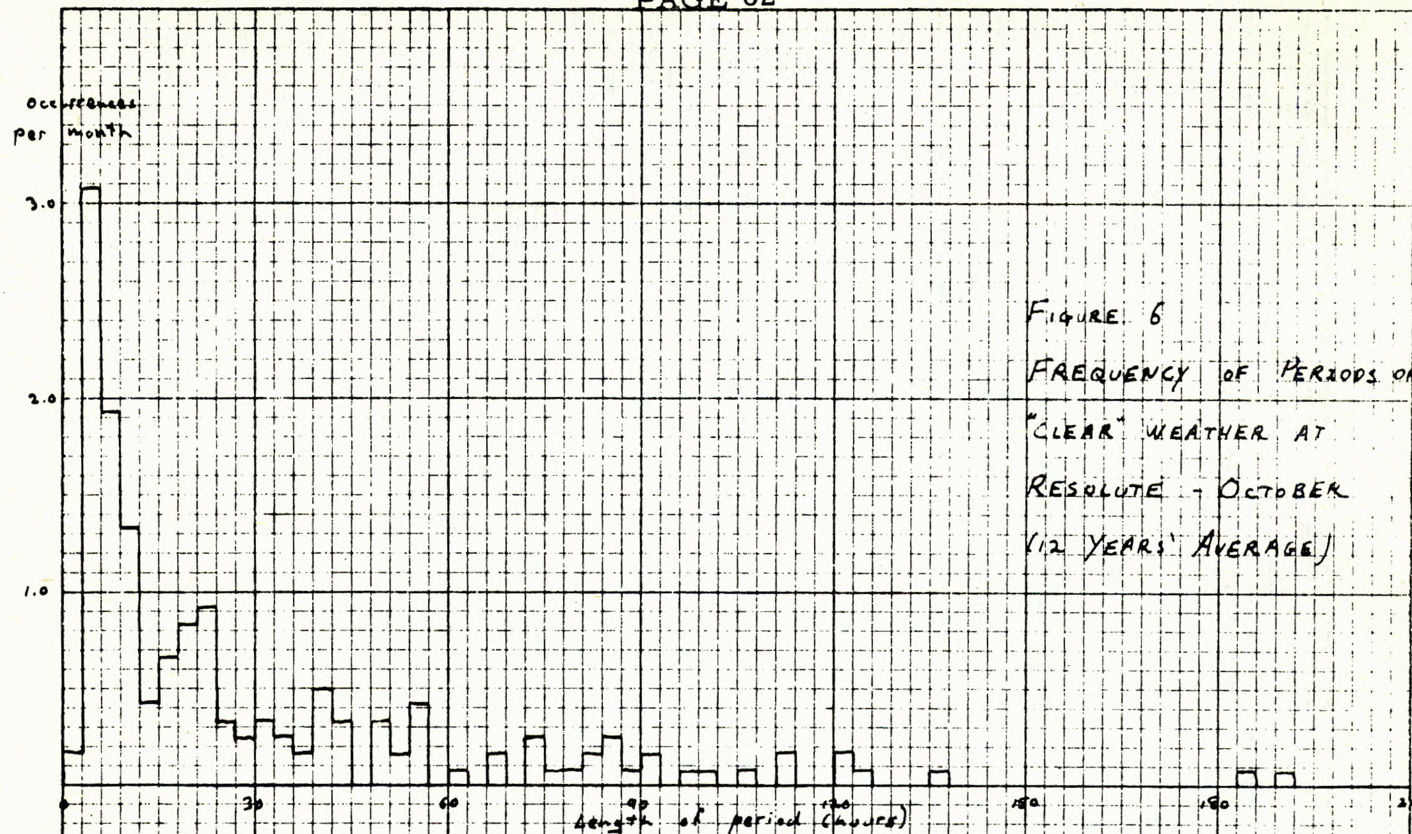

FIGURE 6
FREQUENCY OF PERIODS OF "CLEAR" WEATHER AT RESOLUTE - OCTOBER (12 YEARS' AVERAGE)

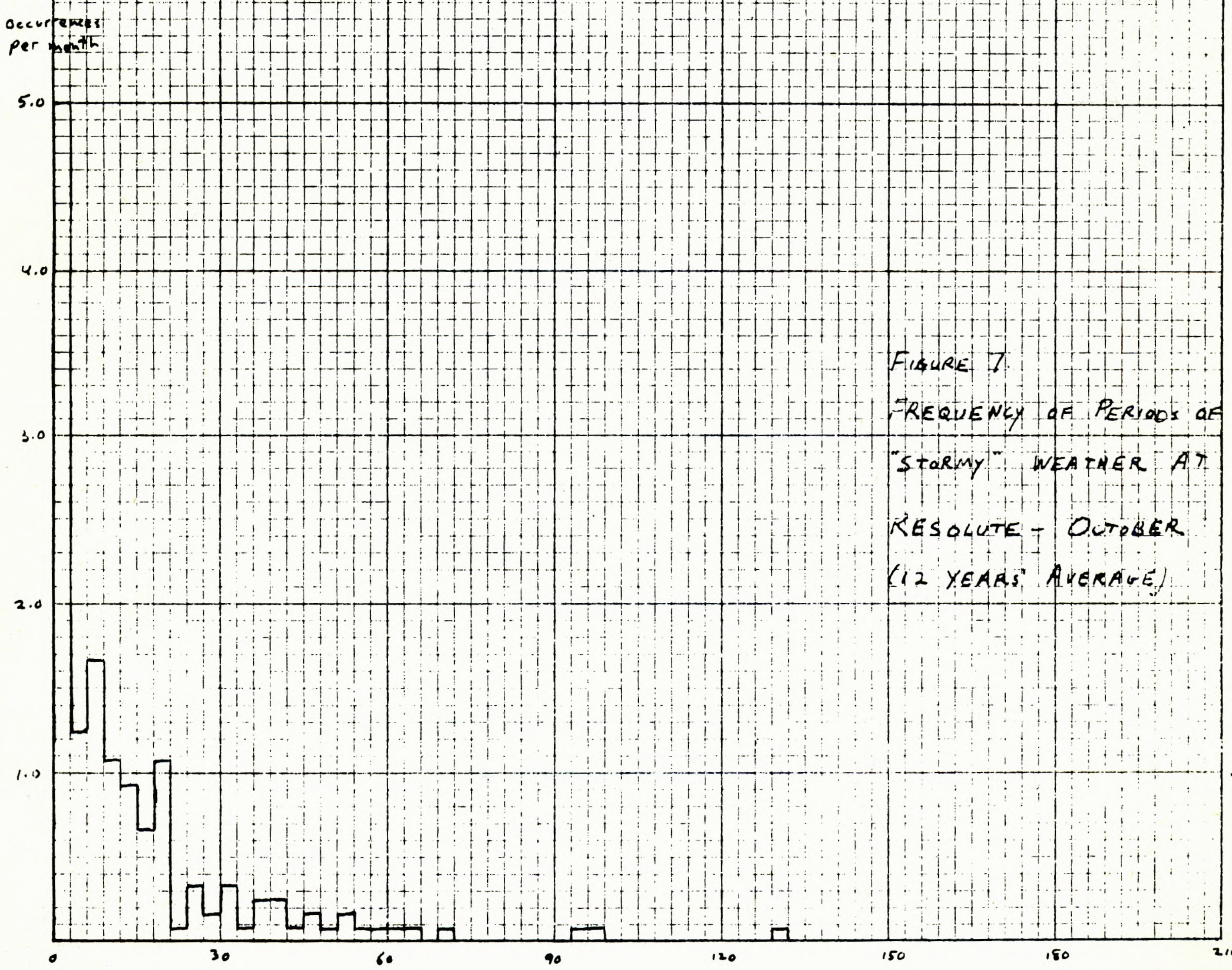

FIGURE 7
FREQUENCY OF PERIODS OF "STORMY" WEATHER AT RESOLUTE - OCTOBER (12 YEARS' AVERAGE)

at a low altitude, there may be an almost complete lack of contrast resulting in loss of depth perception; it becomes impossible to tell, for example, whether an ice ridge is one foot high and ten feet away or ten feet high and a hundred feet away (Harker, 1959: 225).

This situation is rather parlous for the operation of any surface vehicle; furthermore, there is a lack of data showing how common such conditions are. Records kept at Lake Hazen in the winter of 1957-58 (Jackson, 1959: 148) furnish one of the few systematic observations of this phenomenon. These list eight occurrences of whiteout of this type during the period 27 February to 3 June 1958. The duration of the longest periods was from five to seven hours. If this is a true indication of its rate of occurrence elsewhere in the Arctic, we see that it is a troublesome, rather than a critical, factor in the operation of surface vehicles.

For completeness, we may mention two further phenomena which limit visibility. One of these is ice fog, which is primarily caused by condensation around the residue of burnt fuels (Kunai, 1964). In calm weather, which, at many points in the Arctic, occurs for long periods each winter, this dissipates very slowly and can be a great nuisance. It could, conceivably, cause trouble for air-cushion vehicles travelling a much-used route, but it does not seem worth much concern at present.

More serious is sea-smoke, or fog forming over open water in winter. This has the unpleasant habit of being just where it would be easiest for an air-cushion vehicle to go. Apparently it can get quite thick at times; nonetheless, it should not be a complete barrier to the use of the vehicle either.

In summary, we see that there are times - in the case of winter storms, often several days long - when we can hardly use any mechanical form of transport in the Arctic; air-cushion vehicles are no exception to this rule. Apart from such periods, we feel that the available evidence shows the overall weather conditions to be more favourable to the use of a surface vehicle than an air-craft: an air-cushion vehicle would not be held up by low stratus in summer, and it could move along, albeit inefficiently, in foggy weather. Nonetheless, conditions are often so bad that it would be necessary to travel at reduced speed; for an air-cushion vehicle, this brings in the question of excess use of fuel. Furthermore, over rough or unfamiliar ground - over which one would have to go slowly in any event - cross winds might prevent operation entirely. Unfortunately, we cannot judge the seriousness of these problems without actual experience in the field; in the present report we can only adopt the unsatisfactory course of pointing them out as causes of concern and matters for further study.

V

Before attempting to survey the overall utility of an air-cushion vehicle in the Canadian North, we shall pass briefly over the points made in the preceding sections.

In the first place, we have seen that there are, apparently, no overriding technical points which would preclude the operation of an air-cushion vehicle in the winter climate of the Canadian Arctic. There are certain technical problems associated with northern operation, in particular the question of the flexible skirts becoming rigid at low temperatures and the adequacy of the power plant and fan design of existing vehicles for slow travel over rough surfaces. These problems need detailed study, and it is possible that their solution might be so expensive in terms of necessary redesign of the vehicle that it would be impractical, on this basis alone, to use air-cushion vehicles year-round in the north.

Turning next to the terrain, we have come to similar conclusions. It should be possible to operate presently existing machines, with an effective ground clearance of 3 ft. 6 in. to 4 ft. down the Mackenzie River or from Churchill to Cambridge Bay via Baker Lake at any season of the year. With careful choice of route, we should also be able to go from Resolute to Mould Bay, though this might prove extremely difficult. On the other hand, it is also clear that available machines have marginal ground clearance; if this were six feet rather than four it seems that the vehicle could go over most of the impediments to be found on the three routes we have studied. Greater ground clearance presumably means a larger vehicle overall, but here again we cannot at present state quantitatively how important having such clearance would prove in practice.

Both the rough nature of the terrain and the conditions of reduced visibility to be found in the North might require operation at reduced speed. Here it would seem that the air-cushion vehicle is at a serious disadvantage. As can be seen from Table I, present models do not have remarkable range, even at their nominal cruising speed; if we had to travel slowly for protracted periods it would be even less. Although we can, of course, sacrifice payload for endurance, at present we should need fairly frequent fuel caches along any unpopulated route.

Another point which can be raised but not answered is the extent to which the problems of rough terrain and impaired visibility become worse at night. Night-time operation would seem, off-hand, a much more difficult matter, but how much driver acclimatization and a well-marked trail would help is not obvious. This problem will have to be met, for a vehicle which could only be used in fairly good twilight - say the hours in which a car can be safely driven without headlights - would be of quite limited utility in the North for several months each winter. Barring the availability of objective data on this question, though, it is useless to pursue it further.

On all these matters we must remember that it is easy to be too pessimistic. The armchair student cannot hope to evaluate the degree of difficulty entailed in operating any vehicle over rough terrain or in marginal weather conditions; this can only be gained through experience. The fact that air-cushion vehicles are surface craft always affords a margin of safety and means that we can hope to have operation under conditions that look very discouraging on paper.

Let us, therefore, leave aside the questions raised in the last few paragraphs and assume that we have an air-cushion vehicle that is practicable for northern operations. The next question is what it can do efficiently.

To answer this more fully than was done earlier in this report we start with two observations. The first we have already made: currently available air-cushion vehicles are comparable with aircraft. The Westland SR. N5 is quite similar, in terms of payload and horsepower (and hence approximate running costs) to an Otter; projected larger vehicles should be somewhat more economical than a Caribou. Initial costs are high at present [1], but these depend to a large extent on demand, and should not be considered too critically with a new type of vehicle.

Second, we note that air-cushion vehicles, at least as they are presently designed, differ from other surface vehicles in the type of loads to which they are suited. Trucks - or railroads - can handle dense, compact loads, such as ore. The principle of an air-cushion vehicle is to reduce the bearing pressure and spread it over a large area; it is, accordingly, more suited for loads of comparatively low density which can cover a large area (Hughes, S. R., 1964). In other words, it is more practical for transporting so-called "consumer goods" - clothes, household goods, perishable foods. It would be useful for certain types of stock for mines, so that they might not have to build up a whole year's inventory in a few months. It might even be designed

1. The SR. N5, for example, would cost about $300,000 delivered in Canada.

to carry oil, which could be stored thinly over the whole upper surface. At the present time, however, it does not seem particularly suited for the transport of heavy equipment or rock.

Because of this, we do not feel that air-cushion vehicles, in their present stage of development, provide the answer to long-term, heavy duty transport in the North. Roads are expensive to build and maintain (the cost of building a mile of year-round road in the Mackenzie District is roughly estimated at $20,000 to $30,000 (Bourne 1963: 104); this means that there must be a certain amount of expected use to make it worth-while. Accordingly, air-cushion vehicles would seem quite suited economically for use in the initial stages of development of any suitably located mine; but to the extent that the development of the Canadian North depends on base metal mining it seems clear that, for the time being, we shall have to continue to rely on trucks, trains, and ships.

On the other hand, carrying ore is not everything in transportation. One small sideline we have mentioned before: the supply of small field parties. If the terrain were suitable, an air-cushion vehicle should be considerably more economical in such an operation than a helicopter. More important is the transport of consumer goods. Here the settle-ments along the Mackenzie River would furnish an excellent site for present-day air-cushion vehicles to supply a year-round service. The settlements are not too widely separated, so the problem of fuel caches does not arise; in addition, as we have seen in the body of this report, the Mackenzie River valley is a region where both terrain and climate seem quite fitted to the abilities of this type of vehicle.

Along the arctic coast there is also a string of settlements which must be supplied with a certain amount of light goods and oil. Air-cushion vehicles might offer two advantages in serving this area. First, goods must now be trans-shipped [1] ; these vehicles would remove this necessity. Second, it might prove feasible to utilize the amphibious nature of the craft and ship goods from Churchill. In this case, the distance from railhead is considerably shorter; in round numbers, it is about 925 miles from Churchill to Cambridge Bay via Baker Lake, in comparison with approximately 2200 from Waterways via the Mackenzie. Disadvantages are that this route has more fog than occurs on the Mackenzie and that the terrain may offer serious problems. Nonetheless, the savings in expense might make this operation economically sound.

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1. The troubles of trans-shipment are clearly demonstrated by the fate of the barge traffic on Great Slave Lake (Bourne 1963: 102f.). Here, after the opening of the highway, the amount of freight carried by barge has dropped to a low level, even though water transportation is intrinsically cheaper than trucking and, here, is over a shorter route.

In passing, we should not overlook the possibility of using air-cushion vehicles for tourist trips in the North. On the Mackenzie River, for example, they could provide a two - or three - day trip from Hay River to Inuvik. By combining this with a return by aircraft, we would have an interesting and historical excursion.

In conclusion, we give a few comments on directions for further work:

1. The question of skirt flexibility at low temperatures is crucial and deserves serious thought. Some work has already been done on it (Booz-Allen, 1962: 1-85); more - including, probably, some form of laboratory testing - is necessary before cold weather trials *in vivo* become sensible.

2. Present knowledge about ice roughness in various parts of the North is inadequate for the evaluation of the utility of surface transport. In particular, information on the ice on the Mackenzie River and on summer ice in the high Arctic is almost completely lacking.

Unfortunately, it is not clear how we should best proceed to obtain this information. Analysis of air photographs is tedious and liable to produce misleading results. It is necessary to amass a large volume of data on each region; this makes it difficult to study a series of representative types of conditions.

We feel strongly that straight-line scanning - the most obvious way of accumulating information automatically - cannot, of itself, answer the question of the utility of a vehicle which simply goes around many of the higher obstacles. A two-dimensional criterion is necessary; a possible one would give the proportion of the total area which extends more than a given number of feet above the general surface level. To measure this we might combine straight-line scans, say from a laser altimeter, with aerial photographs. Less objectively, one might pick out a suitable route and try to fly along it in a light aircraft and measure heights in this way. Considerable work is needed, however, not only on the size of irregularities to be expected in travel over ice but also on the best way of digesting such information.

3. Night operation of any reasonably fast surface vehicle in arctic conditions is worth studying. Particular questions here are the utility of headlights, both in clear weather and in blowing snow, and the best means of marking a trail.

4. Finally, although we hope the preceding pages have shown the practicability of trying an air-cushion vehicle in the Canadian North, the real extent of its utility can only be decided by actual testing. In

the first instance, extreme cold should not be necessary; its presence would, to a large extent, convert any trials into detailed engineering tests to evaluate the suitability of particular features of air-cushion vehicle design. First trials should contain, as a minimum, operation over rough ice and in the conditions of reduced visibility which occur in the Arctic. Such testing would go far toward showing the soundness of the principle of air cushions as applied to arctic transport.

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