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ICEBERGS AND SEA ICE

Introduction

Ice in the North and South Polar regions is the most outstanding aspect of the polar phenomena which affect man. The age of ice formed from sea water is one to two years, and for iceberg ice formed from snow compressed into glaciers is thousands of years. During winter, the sea ice grows and builds to cover large expanses of the oceans in the northern (5%) and southern (8%) hemispheres. Spring and summer witness melting and retreat of the ice margins. Net water movement equatorward carries ice fragments into all oceans.

The northern reaches of all continents which penetrate the Arctic circle are no longer considered uninhabitable, cold, barren wastes frequented only by wind, snow and bitter cold. During the past two decades thousands of Russians, Canadians, and Americans have temporarily or permanently settled in Siberia, Northern Canada, Alaska and Greenland. Though the majority of U.S.A. influx has been a result of defense reconnaissance establishments for early warning radar and military air bases, the greatest impetus for the Russians has been the economic opportunities afforded by oil, gas, iron, gold, nickel, lead, uranium, mercury, and even diamonds. Polar air routes, commercial and military, are economically important, and major shipping routes from around the world would be shortened in many instances as much as 30% should navigation through the Arctic Ocean become feasible. The Arctic Ocean and associated ice, as well as the Antarctic ice, have a major influence on the climate and week-to-week weather of the world. This article is about the sea ice which covers the North Pole and most of the Arctic Ocean, and waxes and wanes around the Antarctic continent; and about the icebergs which drift over 19 percent of the world oceans.

The Arctic Ocean is a small but deep ocean covering an area of 5.4 million square miles or about 2,500 miles by 1,900 miles on the top of the planet, and the Antarctic is a continent and archipelego of islands all under a two-mile thick ice sheet about 2,500 miles in diameter at the southern pole of the planet. The area of this ice sheet is 5.2 million square miles. Icebergs are pure fresh water pieces of broken-off glacier ice which are the result of thousands of years of snow accumulation over land. Sea ice is frozen ocean or salt water. Both forms of ice have special properties, distributions and histories in the Arctic and Antarctic which are of vital importance to shipping, climate control, man's water supply, marine food and fisheries, and sea pollution.

A tabulation of the volumes and areas of water and ice on the planet is shown in Table I. The majority of the earth's fresh water is tied up in Greenland and Antarctic ice sheets; however, the total amount of ice is less than two percent of the world's fresh and sea water. Nevertheless the quantity is great, as the water equivalent of this ice is equivalent

TABLE I.

	AREA* (X 10^6 square miles)	VOLUME** (X 10^6 cubic miles)	THICKNESS
World Ocean	138	330	
Antarctic ice sheet	5.2	5.8	7,200 ft.
Greenland ice sheet	.67	.62	4,900 ft.
Greenland glaciers	.023	.012	
Antarctic sea ice			
Winter	7.7		
Summer	1.5	5.5×10^{-3}	6-10 ft.
Arctic sea ice			
Winter	4.6		
Summer	3.5	2.2×10^{-3}	10-13 ft.
Western North Atlantic annual melting	.467		
Icebergs Arctic	.003	1.82×10^{-3}	

* Convert to square kilometers by multiplying by 2.59.
** Convert to cubic kilometers by multiplying by 4.16.

to 46,000 years of Mississippi River discharge, or a raising of sea level over 130 feet. The ice sheet that covers the Antarctic comprises 90% of the world's ice. The volume of this ice, some of which is below sea level, is 5.75 million cubic miles (24 million cubic kilometers).

Icebergs are produced at a volume rate of approximately 67 cubic miles per year (280 Km^3/yr) in the Arctic, and 430 cubic miles (1,800 Km^3/yr) in the Antarctic. One can calculate from Table I that icebergs spread over 19% of the world ocean with 93% of the mass in the Antarctic. Fresh water from icebergs is economical in principle as a 10-mile long iceberg could be hauled into the Humbolt current, which flows from the south along South America; thence across the equator to Los Angeles where the cost of iceberg fresh water would be less than the 1970 rates. One iceberg would supply all of Los Angeles for three weeks. Factors of wind effect, break-up, grounding, accessible supply, controlled melting on delivery argue against this venture. Annually about 10,000 icebergs are produced from the West Greenland glaciers, and of these on the average 375 flow south of Newfoundland into the North Atlantic.

The change in reflectivity (known as albedo) of sunlight and, therefore, the amount of heat which is absorbed by the planet plays a vital role in climate. Ice reflects four to five times more sunlight than ocean. The change in areal coverage of sea ice between winter and summer is 1.15 million square miles for the Arctic and 6.3 million square miles for the Antarctic. Thus there is a change in areal coverage of 20% from winter to summer in Arctic sea ice extent, and 80% in Antarctic sea ice maximum to minimum coverage. This winter to summer change in sea ice coverage area is equivalent to twice the area of the United States of America.

Ice Terminology

Bergy Bit	Small iceberg about the size of a cottage.
Brash	Sea ice less than 6 feet in diameter.
Crack	Any fracture or rift in sea ice, but not sufficiently wide to permit navigation. Kinds: (a) tidal; (b) temperature; (c) shock and pressure.
Fast Ice	Horizontal ice formed by the freezing of the sea out from the shore. The 12-fathom contour is approximately the outer limit of the spread of fast ice along open coast lines in the polar basin.
Floe	Sea ice usually 6 feet in diameter or greater.
Small Floe	30 - 600-foot diameter floe.
Medium Floe	600 - 3000 feet
Giant Floe	An area of ice other than fast ice from one-third of a mile in diameter to the limit of visibility from a ship's masthead.
Floeberg	A massive hummock; the result of great pressure and piling up of the heaviest forms of sea-ice.

Glaçon	Any piece of ice other than fast ice, ranging in size from a cake 2 to 3 feet in diameter to a floe.
Growler	A low-lying piece of iceberg ice not so large as a berg or bergy bit. Usually size of a piano.
Hummock	A piece of ice formed by marginal crushing in a heaping up of the sea ice.
Iceberg	A mass of glacier or land ice which has broken off and floats to sea.
Ice Field	An area of ice other than fast ice of such an extent that its limits cannot be seen from the ship's masthead.
Ice Foot	The part of the fast ice that forms and builds on the shore itself and therefore is unaffected by vertical motions such as tides.
Ice or Sea Island	A tabular or flat-topped iceberg tens of miles across.
Lead or Lane	A navigable passage through any kind of ice pack.
Light Ice	Ice less than two feet thick.
Névé or Firn	Loose granular snow in transition between snow and glacier ice.
Pack Ice	Sea ice that has drifted from its original position.
Paleocrystic Ice	Pressure ice, usually more than ten years old, well weathered, and irregularly heaped and tumbled. The type locality is the Lincoln Sea.
Pancake Ice	Pieces of newly-formed ice usually between one and six feet in diameter. The raised rims and the circular appearance are a result of the almost constant rotation and collision of the cakes against one another. Small cakes up to about 18 inches in diameter are occasionally called lily pad ice.

Pinnacled Iceberg	An iceberg that has been weathered and eroded in such a manner that spires or pinnacles extend vertically upward from the main body.
Polar Cap Ice	Oldest and heaviest of ice pack, characterizing the central portions of the north polar basin, usually over three years old and 20 feet thick.
Polynya	Any sizeable water area, not a crack or a lead, which is surrounded by sea ice.
Pressure Ridge	The marginal elevation and heaping up of any kind of pack ice when opposing forces press it together.
Ram	Sloping underwater shelf or ledge of an iceberg or glacier terminus which can extend 50 - 100 feet out from a large melting iceberg.
Rotten Ice	Old honeycombed ice in an advanced stage of disintegration. Through sea water saturation, this ice often appears black.
Shelf Ice	Thick massive coast attached ice sheet consisting of either accumulated perennial sea ice or an extension of land ice, as found north of Ellsmere Island in the Arctic or the Ross and Weddell Seas in the Antarctic.
Snowblink or Iceblink	White glare noted on the horizon from reflection of underlying ice on low clouds.
Water Sky	Dark streaks on the clouds due to the reflection of polynyas, or of the open sea, in the vicinity of large areas of ice.
Young Ice	A compact sheet formed by the repeated freezing of cakes of pancake ice. Its initial thickness is 1 to 3 inches; and this may increase to a maximum, during a winter in the Arctic regions, of 6 to 9 feet.

ICEBERGS

Formation

The formation of icebergs in both Arctic and Antarctic can be understood by visualizing a large accumulation of clay or dough on a table top. As one continues to add dough to the table top, the edges begin to creep out, and eventually some pieces fall off. In this example the dough is the accumulated and compressed snow which turns to ice. As the snow compresses to form firn or névé, the intercommunicating air spaces diminish. At approximately 10% air volume and specific gravity of 0.83, there occurs a transition from firn to ice. This is glacier ice. This transformation takes place at approximately a depth of 200 feet in the Antarctic ice sheet. In colder areas the firn persists to a greater depth. Approximately 95% of the volume of the ice sheet in Antarctica is true glacier ice.

As long as the snow and freezing rain continue to precipitate over a continent in excess of evaporation, glaciers will form and icebergs will break off the glacier terminus and appear in the surrounding ocean. At the point where glaciers or large, extensive ice shelves meet the sea, water pressure beneath the ice shelf or glacier tongue interacts with the outward creeping glacier. The tides, which have ranges up to 20 feet in the Arctic, along with small sea level changes associated with wind and swells, result in an intermittent increase and decrease in force on the protruding end of the glacier or ice shelf resulting in the birth of a large monolith of drifting ice. There are two other ways in which an iceberg is formed. The second way, which is characteristic of Southern Greenland glaciers, consists of a melting or evaporation of the surface portions of the glacier near its terminus at a greater rate than the water erosion. This results in an underwater shelf and eventually, through the erosion of water and periodic tidal and other hydraulic forces, this primarily underwater shelf is broken off and an iceberg floats to the surface. Icebergs of varying shapes are produced in this way. The third mechanism by which icebergs are formed is through the gradual breaking off from the hanging glacier wall or ice shelf. The type of iceberg mechanism is related to the surrounding topography, the climate, and the rate of flow of glacier.

The speed of the ice sheet spread or creep over Greenland and the Antarctic varies from zero near the central continent area of Greenland and the Antarctic to as much as 6 miles per year in the ice streams which make up glaciers. For the same inclination relative to gravity, ice moves 1/10,000 as fast as water. The average movement in the Antarctic is 1,200 feet per year, with most of the measurements between 360 and 3,600 feet per year. These measurements are from glaciers near the coast, and thus are much higher than the average flow rate over the entire history of the Greenland ice cap or Antarctic ice cap. The fastest flowing glaciers have been measured in the western shore of Greenland. The glacier known as the Quarayaq Glacier flows at a velocity between 65 and 80 feet per day, which is twenty times greater than the velocity of most alpine glaciers. Jakobshavn Glacier at approximately latitude 70°N produces 10% of all the Greenland icebergs (approximately 1,350 annually), and flows at about 65 feet per day. The icebergs accumulate in a fjord, and periodically spill from this fjord in groups accompanied by noise which can be heard for several miles. This greatest iceberg producing glacier is only 4.4 miles along its front, 300 feet above sea level. In contrast to the rapid moving glaciers, the very wide glaciers that move slowly produce only very small icebergs and ice chunks (bergy bit). Some glaciers, for example the Frederickshaab with a twenty-mile front, have rates of flow equal to the rate of melting, and thus produce no icebergs. The annual yield of icebergs in the Arctic is, at the most, 15,000, with only approximately 5,000 of sufficient size to reach the open ocean intact.

The largest glacier in the Northern Hemisphere is the Petterman Glacier, 81°N 62°E. Although it is only a few yards above sea water, its ice foot extends out as far as 25 miles to sea, and pushes a path through old piled up sea ice. These long fingers of the glacier ice in the severe climatic conditions, somewhat protected by sea ice, break off once every ten to twenty years. Another glacier of importance is the Ungersen Glacier in Northern Greenland. This glacier and the Petterman Glacier produce very large tabular icebergs, known in the Arctic as "ice islands", which are similar in shape and technique of formation to the large tabular icebergs of the Antarctic, but much smaller. East Greenland icebergs normally move northward. The icebergs of Eastern Greenland have little practical importance in that they are small in size and number. The icebergs that do leave the fjord and the coast area enter the East Greenland current, and some join the West Greenland icebergs. The icebergs which reach the North Atlantic Ocean from Northern Greenland, Siberia, and Northwest Territories constitute less than 10% of the total icebergs produced in the Northern Hemisphere. They are of little importance in that they do not affect the sea routes and, other than formation of ice islands, have no importance to man. The majority of icebergs that originate from Western Greenland are of great importance to man in that of a total annual production of approximately 7,500 icebergs (total for Arctic is 10-15,000), 800 to 1,000 are carried into the open ocean by the Labrador Current.

Size and Distribution of Icebergs

Probably the first mention of icebergs was that of St. Brendan, an Irish monk whose partly fiction writings suggest he encountered a "floating crystal castle" on the high seas. After calving (breaking off) the Greenland and Antarctic ice sheets and smaller outlying glaciers, icebergs can move thousands of miles through the Arctic in a few years, and slip down along the eastern North American coast to be caught up in the Gulf stream and, while melting, carried in a few weeks to within a few hundred miles of England and Ireland, or by a combination of wind and current to Bermuda, as happened in 1907 and 1926. These and other rare sightings are shown in figure 1.

Of the 10,000 to 15,000 icebergs calved from glaciers annually in the Arctic, only 375 on the average pass Newfoundland or latitude 48°N into the North Atlantic Ocean. Some years over 1,000 are seen, and other years less than 30 are sighted. The yearly average has diminished over the last 20 years, and for the last 10 years there has been a marked decrease in the number of icebergs sighted in the North Atlantic. The average distribution of these icebergs in April, May, June and July is shown in Fig. 1. There are few icebergs in the Arctic basin proper. The major source areas for icebergs in the Barents Sea is Franz Joseph Land. Icebergs are not found in the North Pacific except in sounds along the Alaskan-Canadian coast between 55°N and 60°N latitudes.

Arctic icebergs vary in size from the size of a large piano, called growlers, to the dimensions of a ten story building. Icebergs the size of a small house are called bergy bits. Many icebergs in the Arctic are about 150 feet tall and 600 feet long. Icebergs of the Antarctic not only are far more abundant, but are of enormous dimensions compared to Arctic icebergs. Ninety-three percent of the world's mass of icebergs is found surrounding the Antarctic.

Other than Arctic basin ice islands, the largest iceberg noted in the northern hemisphere was 7 miles long and 3.7 miles wide sighted near Baffin Land in 1882. The largest Arctic iceberg sighted south of Newfoundland was encountered by a whole convoy during World War II at $43^{o}10'$N and $49^{o}33'$W. There were multiple collisions and much confusion before all ships safely limped into port. This ice island was 4,500 feet long, 3,600 feet wide and 60 feet high. These icebergs are similar in size to Antarctic icebergs, to be discussed below, but by and large only a few large tabular icebergs are seen in the Arctic as compared to the predominance of the tabular icebergs noted in the Antarctic. The tallest icebergs measured were 447 feet high by Drygalski in 1895, and an iceberg 527 feet tall was measured and photographed from helicopted by the U. S. Coast Guard in the late 1950's. The icebergs of Eastern Greenland are smaller than those of Western Greenland.

In the southern hemisphere the maximum limit of iceberg drift is 1,000 miles further north than the northern extent of sea ice in the Antarctic (Fig. 2). Most icebergs are concentrated south of the Antarctic convergence about 60^{o}S.

Some icebergs from the Antarctic continent ice shelves drift north of 42°S latitude in the Atlantic sector of the southern ocean, but only to latitude 56°S in the South Pacific Ocean. One Antarctic iceberg was sighted only thirty miles south of the Cape of Good Hope (Africa) in 1850. The furthest northern extent of ice sighted in the southern hemisphere was at position 26°30'S in longitude 25°40'W.

Antarctic icebergs are characterized by their tremendous size and tabular or table-top shape. Lengths up to five miles are not unusual, with ice 150 feet above water. The discovery of the origin of these immense tabular bergs was made by Ross in 1841 when he penetrated the Ross Sea and encountered the Ross Ice Shelf, which he discovered was afloat. Most Antarctic icebergs are formed from the Antarctic continental ice sheets as it thins toward the coast and exudes into the ocean as a great ice shelf with fronts hundreds of miles long. The four major ice shelves are the Filchner shelf in the Weddell Sea, the Ross Ice Shelf in the Ross Sea, the Shackelton Ice Shelf in the Indian Ocean sector, and the Larsen Ice Shelf on the Antarctic Peninsula (also known as Palmer Peninsula and Graham Land). Antarctic icebergs, if they remain locked in the pack ice, will last for many years. One of the largest icebergs sighted was over 90 miles in length. This tabular iceberg was first sighted in 1927 and presumably the same iceberg was later seen in 1931, at which time it was 60 miles in length. The largest known Antarctic iceberg was measured by the icebreaker USCGC GLACIER in 1956, during the International Geophysical Year. It had a length of 208 miles and a width of 60 miles.

Age of Icebergs

Greenland icebergs 1,000 to 1,500 feet thick represent several centuries of precipitation. This figure is based on the comparison of the thickness of the ice sheet to the known or average annual precipitation of, say, 8 to 24 inches per year in the source area for icebergs. Age of ice in central Greenland close to bedrock is estimated at 30,000 to 150,000 years old. The longest core retrieved from the Greenland ice sheet was 4,580 feet long with a bottom date of 100,000 years. It is probable that the oldest ice melts before reaching the outlet glaciers. One can estimate that the mean age of icebergs is 5,000 years from the known amount of precipitation over Greenland, and the assumption that the ice volume and precipitation rate now are approximately the same as were present many centuries ago. Measurements by carbon-14 dating of entrapped air show that icebergs are hundreds to thousands of years old--the oldest actual measurement being 3,000 years. Arctic ice islands and Antarctic giant tabular bergs last as long as 10 years at high latitude. The majority of icebergs from Western Greenland melt within two years of calving from the parent glacier.

Melting of Icebergs

Once an iceberg has been calved and moves out of the fjord into a bay and thence the open sea, it sojourns in Baffin Bay for three months to two years, during which time it undergoes some disintegration through melting and calving of small chunks of ice from its perimeter. This results in a decrease in mass of about 90% by the time it reaches the coast of Newfoundland and the Grand Banks in the North Atlantic. When the iceberg enters the region of the Grand Banks, where the warm 80° waters of the Gulf Stream meet the colder waters of the Labrador Current, it has only a few days of life remaining. A large iceberg 400 feet long was noted to melt within 36 hours in 80° water. The estimated rate of iceberg melting is based on the observation of a number of individuals from the International Ice Patrol. For mild sea conditions an iceberg deteriorates at a rate of height decrease of 6 feet/day in 32°F to 40°F water, and 10 feet/day in 40°F to 50°F water. Destruction of icebergs in warm water is increased during stormy weather, when mechanical erosion of icebergs is added to the thermal effects of air and water. During the erosion process icebergs usually take on the form of a saddle, because erosion at one pole of the major axis of the iceberg results in that point rising, while the other end of the major axis is being eroded. Subsequently the latter end, due to loss in weight, arises and this rocking back and forth continues while constant erosion is occurring along the minor axis leading, usually, to a bipeaked or saddle-shaped structure. Table II is an estimate of the time necessary for deterioration, and is based on unpublished quantitative measurements in 1960 and general observations by ice scientists.

TABLE II.

Deterioration or melting time in days for icebergs at 45°N(estimated).

SEA WATER TEMPERATURE	SIZE OF ICEBERG	
	80 feet high 300 feet long	Greater than 150 feet high & 500 feet long
32	40	80
40	10	20
70	4	8

Wind and Current Effect on Icebergs and Sea Ice

Iceberg movement is influenced by direct wind push on the exposed sail area to an extent far greater than commonly assumed. Although the majority of the iceberg is below water, in many situations wind has a dominant influence on the movement. The wind intensity and direction over Baffin Bay in the spring of one year influences the number of icebergs which slip into the North Atlantic that year and the following year. This can be understood by noting that icebergs pouring out of the Arctic north of Newfoundland in spring will run aground or be trapped in the ambayments of Western Baffin Bay unless wind and current deflect their set southeast. However, of more importance is the effect of wind over Western Greenland, where intense offshore early summer winds over the ice fjords drive sea ice entrapped bergs into the West Greenland current, thus increasing the number of icebergs which, having made the usual counterclockwise circuit, will arrive off Newfoundland the following spring. The late Admiral E. Smith and subsequently I. Snell have shown reasonable correlations between atmospheric pressure distribution of one year and the number of icebergs drifting south of Newfoundland in the following year.

The day-to-day movement of an iceberg is controlled by the iceberg size and shape, previous and present wind, surface wind current and ocean gradient current. The most important factor in assessing wind drift of icebergs is size and shape. Although most icebergs have a specific gravity of 0.9, and thus 6/7ths of the mass is below the sea surface, it is not true that this means that a 100-foot high iceberg is 600 feet deep in all cases. This is true only for the rectangular, blocky, or flat-topped icebergs common to the Antarctic. Table III. gives the relation between exposed and underwater areas for various shapes of icebergs.

TABLE III.

Exposed to submerged proportions
and wind factors for icebergs.

Iceberg Description	Proportions Exposed : Underwater	Wind Factor
FLAT-TOPPED or BLOCKY	1:6	.004
ROUNDED or DOMED	1:4	.005
USUAL GREENLAND ICEBERG	1:3	.01
PINNACLED or DRYDOCK	1:2	.03
WINGED	1:1	.04

Winged icebergs are very much influenced by the winds, and move at speeds of 1 knot or 24 nautical miles/day under the influence of steady winds of 30 knots. The wind force on an iceberg does not result in movement directly downwind, but because of the rotation of the earth (Coriolis force) windage on an iceberg is 30 to 50 degrees to the right of direction toward which the wind is blowing. This remarkable deviation rightward in the Northern Hemisphere and leftward of the wind set in the Southern Hemisphere was first noted by Fridjoft Nansen during Arctic observations of icebergs in the late 1890's. The physical and mathematical theory which accounts for this was later developed by Ekman and Nansen. In addition, the momentum of icebergs is so great that once in motion they continue for hours after the wind has abated. It is possible for an iceberg to be driven before a 30 knot wind at 1 knot in a direction 30 degrees to the right of the wind, and after the wind stops the iceberg will slow and circle in what is known as an inertial circle associated with the rotation of the earth. The iceberg near the Grand Banks will be moving in a direction opposite to that toward which the wind was blowing about eight hours after the wind stops; however, the speed would be low and such anomalous movement would not be observed unless the initial speed and momentum are great. A careful accounting of berg underbody dimensions, relationship of wind-current forces and iceberg mass will lead to explanations of anomalous iceberg movements. To emphasize the importance of wind effect and its prediction, one potentially disastrous case will be cited. In 1960 a 200-foot high 1,000-foot long iceberg was driven off the tail of the Grand Banks into the shipping lanes by northwesterly winds averaging 50 miles per hour. This iceberg moved 90 miles at as much as 3 knots across the Labrador current and resulted in an emergency move of the North Atlantic shipping lanes further south.

The drift of icebergs and sea ice is the result of the ocean current and the wind. When the winds are variable or less than 20 miles/hour, and the current greater than 0.5 knot, the current predominates, but when steady 30 knot winds blow ~~steady~~ for more than 12 hours, the wind effect becomes important even in areas where the ocean current is 1 to 2 knots. In addition to windage on the iceberg and ocean gradient current, the wind induced surface current has the effect of increasing drift speed by about 10% for small icebergs, and increasing the angle of drift direction.

Sea ice drift is better understood, but in some respects more complicated than iceberg drift. In addition to size, inertia, and exposed-to-underwater dimensions, important additional information on surface roughness, water drag and internal resistance due to ice field concentration is needed to describe the motion. The observations of the Americans and Russians drifting on ice islands in the Arctic basin, Baffin Bay and Gulf of St. Lawrence, along with Japanese and Russian long-term ice field observations, are summarized in Table IV. As noted from the table, ice fields consisting of 10% ice and 90% open water will move at 1% to 8% the surface wind velocity. The angle of drift is from 20 to 40 degrees to the right of the wind in the Northern Hemisphere. The speed will be reduced by a factor of 4 as the ice becomes packed to 90% coverage of the ocean. Smooth ice drifts with less speed than rough ice because of difference in wind coupling. However, usually rough or hummocked ice is thicker and thus has greater inertia. Ice of great inertia takes longer to reach the wind factor speed, but, after the wind stops, continues to move longer than light ice. This phenomenon results in strings of ice floes aligned perpendicular to the wind with small floes packed to windward against larger floes. This wind sorting of ice is a phenomenon of great importance in navigating pack ice and, as suggested by the great Russian ice scientist N. N. Zubov, the strips of open water aligned in a direction approximately perpendicular to the direction of wind explains the successful navigation in ice performed by sailing vessels in the past.

TABLE IV.

Wind factor for speed of sea ice drift.

% Sea covered by ice	Rough hummocky surface	Smooth floes
	Wind factor	Wind factor
10	.08	.01
50	.05	.005
90	.02	.003

Iceberg Detection

In the open ocean most ice is seen by radar at ranges depending on their size, but smaller icebergs or growlers can only be detected when the sea surface is calm, and then only at ranges in the order of one mile. During slight wind conditions, in particular in the heavy seas, the echoes from the waves, known as sea return, may completely mask the echoes of large, potentially very hazardous chunks of ice. In addition, the radar return from rain and snow obscures the return from ice in either rain, snow or fog conditions. Neither radar nor sonar can be relied upon for detection of icebergs and pack ice in choppy seas. The reflectivity of ice and snow to light is great, but reflectivity to radar or short radiowaves is very poor. This phenomenon is due to the electrical characteristics of ice. Fresh water ice has a dielectric coefficient of 3.5 and a commercial radar wave length reflectivity of only 0.2; whereas, the reflectivity of sea water is greater than 0.95, similar to that of metal. Thus as U. S. Coast Guard studies showed, a metal ship less than two percent the size of a typical iceberg reflects radar better, and is thus more easily detected. Of more relevance is the fact that an iceberg 22 feet high cannot be detected with modern equipment if the waves are over four feet high. Thus it is not surprising that the modern HANS HEDTOFT collided with an iceberg and sank in heavy seas. Various innovations since the inception of radar during World War II have not improved significantly the capabilities of radar to detect icebergs, thus ships are still bound by international agreement to proceed at slow speed in fog.

Sonar is effective in detecting icebergs; however, the range of detection is frequently limited by the water conditions, and speed of commercial vessels. The likelihood of insufficient warning for high speed passenger and cargo ships leaves this mode of detection inadequate. Other suggestions of dropping radio transducers or metal reflectors onto icebergs have the common fault that they are subject to iceberg rolling over and calving, which are frequent occurrences as the dying iceberg melts its way deep into the warmer waters of the shipping lanes.

Thus the problem of iceberg protection comes to tracking icebergs as they come down the Labrador Current, and reporting the whereabouts of these floating deadly menaces to all North Atlantic shipping as often as twice daily. This sometimes involves keeping track of 300 icebergs and requires a team of iceberg experts, oceanographers, aviators and seamen. During heavy ice conditions two U. S. Coast Guard planes fly six to eight hour reconnaissance missions from Argentia, Newfoundland, over the Grand Banks off Newfoundland and contiguous areas. Positions of icebergs are plotted and correlated with previous positions of the same icebergs or groups of icebergs. When dangerous icebergs approach the shipping lanes, a ship departs for the scene to standby near the iceberg and warn approaching ships.

Iceberg Destruction

Once an iceberg is spotted in a position of threat to ships, it should be of no harm if destroyed. However, destroying a 200,000 ton block of ice is a task whose difficulties leave it impractical in most situations. The first successful results on breaking up icebergs by explosives were reported by the late Professor H. T. Barnes of Canada in 1929, when he reported a few hundred pounds of thermite through thermal stress cracked an iceberg into smaller pieces which melted more rapidly due to the greater surface area exposed. Similar thermite experiments by the U. S. Coast Guard on two icebergs in 1959 did not corroborate H. T. Barnes' findings. Attempts at bombing, torpedoing, shelling, and even ramming have been unsuccessful. Imagine an office building made of solid walnut being hit by a 1,000 pound bomb--some damage to a surface corner might be seen. Now imagine that an additional 6/7ths of the walnut mass was underground. With twenty 1,000 pound bombs acting as direct hits, or as depth charges, it is possible to chip away about 20% of a 250,000 ton iceberg. The International Ice Patrol has even tried painting half of an iceberg with lamp black or charcoal to induce thermal stress. The experiments were inconclusive. Other means, such as nuclear depth charges or torpedoes, suffer from unacceptable consequences.

Sediment Transport

Both icebergs and sea ice transport sediment, pebbles, boulders and even plant and animal life thousands of miles from the source area. The distribution of icebergs 10,000 or more years ago can be inferred from pebbles, cobbles, and boulders widely disseminated on the ocean floor of the North Pacific Ocean as far south as 48°N latitude and in the South Atlantic Ocean as far north as the latitude of the Cape of Good Hope in the southern hemisphere. Ice rafting competes with kelp rafting as an explanation for the occurrence of pebbles and boulders on the sea floor as far south as Baja California, and other areas of the world ocean.

Bottom freezing of ice shelves and ablation of the ice surface results in migration of sediments and organisms upward. Layering of sediment can be seen in sea ice floes and icebergs from ice shelves. Fossil penguin bones have been found as far north as 30°S and massive banks of boulders have been noted on the sea floor off South Africa. Sediment thicknesses of as much as 50 inches of glacial till have been noted on the ocean floor from discharge by icebergs, apparently during the last one million years.

Icebergs are colored brown, black, and green by a combination of sediment, plankton deposits under the source area ice shelf, and glacial blue ice.

SEA ICE

Formation

On superficial examination, frozen ocean or salt water appears similar to fresh water ice; however, there are two principal differences. In the first place, because the maximum density of sea water is below the freezing point, even after freezing the water below the ice will continue to turn over. As the surface water near the ice becomes colder, it becomes heavier and sinks, resulting in a continuous turnover or vertical circulation of the water beneath the ice. This is a different situation than occurs in lakes where, because the maximum density of fresh water is above the freezing point, once ice forms the colder water is lighter than the deeper somewhat warmer water, and mixing does not occur. A second characteristic is the fact that as sea water freezes, minute pools of salty water called brine pockets are entrapped. The final form and the macroscopic physical properties of the ice are very much dependent upon the concentration of the brine pockets within the ice block. Once an ice field has formed, the physical and chemical properties are not locked in a frozen coffin, but vary as brine pockets migrate through the ice block in response to gravity and thermal gradients.

In the Northern Hemisphere during September and October , the air temperature lowers sufficiently to form a thin sheet of ice. Freezing temperature for average northern ocean salt water of about 3.5 percent salt composition by weight (usually designated 35 parts per thousand) is 28.7°F. The first signs of freezing are changes in the color and texture of the sea surface as thin, gray colored needles and crystal plates form a surface thin sludge. If quiet sea conditions prevail, sheets of crystalline aggregates plate the ocean surface. Initially the ice film is entirely fresh, but as more ice crystals form, pockets of salt water (brine pockets) become entrapped between lamellae of tiny ice plates. The amount of brine entrapped depends on the temperature of formation and the age of the ice. The shape of the initial ice crystals varies from square discoids to hexagonal dendritic forms. The average width is 1 inch and the thickness up to about 0.06 inches. During the surface veneer formation stage the optical or C-axis is perpendicular to the water surface, and each grain is free to grow both laterally and vertically until the sheet consolidates. As the ice sheet thickens, the process of geometric selection results in a transition of crystal orientation to a C-axis horizontal configuration. Due to slight breezes and water motion, these thin sheets of ice jostle about and, after but a few hours, form a field of ice paddies. The appearance is very much similar to a lily pond completely covered with large gray lily leaves with slightly raised white fringes around their periphery. These discs of ice are known as pancake ice. If the temperature remains below freezing, the pancake ice coalesces as more ice forms, and within a few days the ice cover can be three to four inches thick with a slightly corrugated surface, unless snow prevails, in which case the entire sea area appears as a smooth white plain. As sea water continues to freeze at the bottom edge and sides of ice floes and fields, snow cover increases and the pressures associated with the stresses and strains caused by water and wind movement result in a hummocking and ridge development in some places and open water in other places.

The rate at which the ice forms and thickens depends on the air temperature, ocean turbulent heat flux (mixing conditions) and amount of snow acting as a heat or cold insulator. An empirical formula has been developed and used extensively by the Russians and Americans to predict ice appearance and growth rate. The equations are based on the simple concept that ice growth is directly related to the time duration during which the air temperature is below the freezing point for sea water. By adding the number of Fahrenheit degrees below the freezing point for each day, one has a measure of the severity of cold and time of exposure. This measure is known as the freezing degree days. In north polar regions there are about 8,000 freezing degree days, which is equivalent to four months of 0°F air temperature or a mean annual Arctic air temperature of 10°F (22 degrees below freezing).

During ice growth there is surface evaporation and sublimation and bottom ablation when upward heat conduction in the ice is less than ocean upward heat conduction. The balance between ablation and freezing or accumulation results in an equilibrium thickness of about 3.5 meters ice in the Arctic and probably about the same in the Antarctic. The lifetime of this North Polar sea ice is 5 to 8 years, and the lifetime of Antarctic polar class ice found only in the Bellinghausen and Weddell Seas is about three years. These lifetime values are related to the rate with which the whole Arctic or Antarctic pack in certain areas moves equatorward.

Sometimes early in the season there is sufficient warming and wind induced surface motion to completely disintegrate the ice field. Oftentimes after four or five inches of ice and snow have been formed in a more-or-less uniform manner, a large crack develops which, through wind and stress, opens into a wide canal commonly known as a lead. This phenomenon is seen frequently in older ice and during the spring break-up. Leads are frequently followed by ships navigating in ice fields, but unfortunately sometimes leads have a dead-end with a very large iceberg blocking the way. With alternating freezing, partial melting, snow and wind and swell, the ice field develops over a matter of a few weeks to a month into a six inch to two foot deep ocean cover. At this point the ice field is still navigable by most large vessels; however, if a vessel finds itself in the far north two weeks after the commencement of active surface freezing, e.g., in late October, it is in peril of being locked in for the remainder of the winter. During this macroscopic evolution of an ice field, the microscopic characteristics of the ice itself are under active change.

Saltiness of Sea Ice

The salt content of sea water as it freezes is always less than that of normal sea water. The amount of salt in the sea water during its first moment in the solid state is dependent upon the rapidity with which the sea water freezes, but in general salt content is about one-tenth that of sea water. The slower the freezing process, the less the salt content. The most rapid freezing is that which occurs during the first day, and this ice is saltier than underlying ice which forms at the ice water interface. The salt that remains in the ice is located in tiny pockets of fluid surrounded by normal crystals. These pockets of fluid migrate by mainly gravity through the matrix of ice crystals and, after a few weeks to a few months, the surface of the ice becomes lower in salt content than the deeper layers. It has been thought by some that the difference in temperature, thermal gradient, was perhaps the principal driving force for the brine pocket migration; however, careful experiments indicate that although the thermal gradients are a factor, it is in the main gravity that accounts for the movement of these brine pockets.

Brine pockets are approximately .2 mm in diameter, and move at approximately .008 mm per hour. The ratios between the more abundant substances in sea ice are not significantly different from those of sea water itself, and remain essentially constant in freezing and migration as long as the temperature of the ice is above -8°C.

In the summer, when the ice temperature rises, there is a rapid increase in the migration of salt out of the ice, and the sea ice surface becomes potable, and in fact is used by Eskimos as a source of fresh water. Salinity reaches a value of less than .01 percent. In summary, when first formed the surface layer may have a salinity of two to four percent, but by April the salinity has dropped to between 0.4 and 0.7%, while sea ice that has been through at least one melt season has a ~~salinity~~ salt content below 0.1 percent.

Arctic Sea Ice

The sea ice of the northern hemisphere covers an average area of 4,100,000 (see fig. 1) square miles filling the Arctic Ocean basin and adjacent North Atlantic Ocean. The polar ice field is comprised of 1,800,000 square miles of 10 to 20 foot thick polar ice which never melts; however, infrared imagery from aircraft shows that 10% of the polar pack is open water even during winter. Along with Arctic basin seasonal sea ice, this Arctic pack exudes into the Northern Atlantic through two ice streams. The major exit of drifting pack ice from the Arctic basin is along the eastern side of Greenland, mostly west of Spitzbergen. This ice tongue stretches 1,500 miles out of the Arctic Ocean and empties a stream of sea ice at a drift rate of eight miles/day. The second icy arm of the north consists of a discharge ~~along~~ ~~and~~ through the Arctic-Canadian archipelago and along eastern American shore. This out-pouring of ice is the principal deterent to easy Northwest Passage ship transit and Northern American migration and exploration. During winter, fast ice and local sea ice form along the Siberian Coast, Barents and Kara Seas, East Greenland and Labrador coasts down to Newfoundland. The maximum extent of drifting sea ice is about 42^{O}N latitude (about the same latitude as Boston); however, this represents the limit of floating ice pieces, and not the hazardous ice pack edge, which seldom reaches south of Newfoundland. During the summer, the winter 150-mile belt of ice lying along the Labrador coast from Newfoundland northward melts to leave the approaches into Hudson Bay and the Canadian Northwest Territories clear.

The motion of the polar ice follows a giant clockwise eddy with a center 85°N 170°W. This motion was noted during the trans-Arctic basin drift of F. Nansen's FRAM, which was purposely locked in the pack north of New Siberian Islands and drifted 1,400 miles to Spitzbergen.

In the North Pacific Ocean comparatively little sea ice and icebergs are encountered. The Bering Sea is clear of sea ice during the northern summer, but commencing in September sea ice forms in bays and is carried through the Bering Strait. In winter and spring sea ice is found as far south as 40°N. This is drifting ice from northern latitudes and the Sea of Okhotsk. During winter sea ice forms in the northern part of the Sea of Japan.

Antarctic Sea Ice

About two times more sea ice forms in the southern ocean surrounding Antarctica than is found in the Arctic; however, there are only limited regions in the Bellinghausen and Weddell Seas where true polar perennial ice is found similar to the polar ice ~~perennial~~ cap which occupies most of the Arctic Ocean (fig. 2). The maximum area of Antarctic pack ice is 7.7 million square miles or 8% of the southern hemisphere.

The major work on the Antarctic sea ice distribution was published in 1940 by MacIntosh and Herdman. This was the first complete circum-Antarctic chart of the sea ice distribution based on the positions of the ice edge reported by whaling factory ships, various expeditions, and the observations of the Discovery Committee's vessels. Figure 2 is an indication of the extent of sea ice based on their studies. This information has been supplemented by more recent observations, primarily since the International Geophysical Year, 1957. The Antarctic pack ice forms a more-or-less constant width band of drifting sea ice around the continent (Fig. 2) with the furthest northern extent at the end of the Austral (southern) winter in October. The greatest extension of sea ice in the South Pacific sector is found in about latitude 62°S, and in the South Atlantic sea ice extends to 52°S. The average northern boundary for icebergs is 56°S in the Pacific Sector, and 42°S in the South Atlantic Sector. The minimum ice coverage occurs in March when most of the Antarctic coast is free of ice, with the exception of the Weddell and Bellinghausen Seas. The eastern and western coasts of the Weddell Sea are ice free, but the Weddell Sea itself is covered by a slowly clockwise revolving pack which seems to have a two-year cycle. The west coast of the Ross Sea is the most predictably open area during the Antarctic summer, and it is here at the approaches to McMurdo Base that most of the Antarctic expeditions have worked their way to the continent. Much of the sea ice encountered in November and December on approaching the continent hundreds of miles from land fall represents ice that formed near the coast from the previous Austral winter. Usually in January and February there is clear water adjacent to the coast in all sectors around the continent, but this navigable water might be blocked by hundreds of miles of pack ice barrier further to sea. The Antarctic freeze-up commences with sea ice formation in the southerly parts of the Weddell Sea followed by sea ice appearance in the Bellinghausen and Ross Seas. Commencing in March ice is formed in sheltered bays, and extends north as the sea surface temperature drops. During the period from late February to August, snow fall adds more to the ice thickness than is the case in the Arctic. This is an important difference between Arctic and Antarctic navigation,in that the presence of snow has a cushioning effect, and ice breaking is more difficult. By the October maximum the action of wind, sea and some melting results in very active ice movement. It was in October, after a winter of peaceful wintering fast in the ice, that Sir Ernest Shackelton's ship ENDURANCE was crushed and sank in the Weddell Sea.

The movement of the entire ice sheet around the Antarctic continent is from east to west except in the most northern part of the Weddell Sea, where there is a west to east movement making up the northern arm of the Weddell Sea gyral. This clockwise Weddell eddie has been well documented by the drifts of the entrapped ships DEUTSCHLAND, ENDURANCE, and THREON. The ice drift in the Bellinghausen Sea is less definite. The ship ANTARCTIC followed a meandering, aimless course when locked in the ice throughout the 1898-99 winter. From the Ross Sea, ice definitely drifts toward the Weddell Sea under the influence of the prevailing easterly winds near the Antarctic coast.

PHYSICAL PROPERTIES OF ICE

Crystallography

Ice crystallography has been the subject of study by x-ray, neutrons, and electron defraction. The general crystallographic structure of ice can be visualized by assuming the oxygen atoms as being arranged in sets of interlocking tetrahedra. Thus each oxygen atom is surrounded by four equally spaced oxygen atoms at the vertices of a tetrahedron with a resulting hexagonal symmetry. The a axis is 4,523 angstroms, and the c axis is 7.367 angstroms. The distance between oxygens in the tetrahedral structure is not constant for each oxygen; thus there is not perfect tetrahedral symmetry. The hydrogen atom lies on or almost on the axis between each oxygen, but is not located midway, but approximately one angstrom from oxygen from either end of an oxygen bond. The index of refraction is 1.31 for pure ice at optical frequencies.

Mechanical Properties of Ice

The flexure stress of pure fresh water ice is approximately 240 lbs./sq. in., and the compression stress is approximately 500 lbs./sq. in. The tensile strength is about 150 psi. These apply to ice samples whose minimum dimension is 5 cm, temperature -5°C. The texture and tensile strength of sea ice are approximately one-third the fresh water ice values. The strength of sea ice varies with the amount of brine and temperature. The tensile strength of ice is related to the square root of brine content. These values are of not great use estimating the most important practical strength of ice, the bearing strength for landing aircraft, constructing shelter and movement of men in vehicles across sea ice. For brief duration the ice behaves elastically with the greatest stresses developing in the warm layers. The bending of the ice is somewhat offset by the buoyant force of water. The elastic properties of ice characterized by the Youngs modulus is usually calculated from seismic observations on floating ice covers. Here again the value is dependent upon the amount of brine present, and ranges between 2 and 10×10^{10} dynes/cm^2.

Density of Sea Ice

Pure ice at zero degrees centigrade and one atmosphere of pressure has a density of 0.9168 gm/cm^3; however, naturally occurring ice from glaciers, icebergs, sea ice, and lake ice contain air bubbles, and this lowers the specific gravity to as much as 0.86. The density of ice is also related to the temperature through the coefficient of volume expansion. The measured density of sea ice varies from 0.85 to 0.94 depending upon the brine content and temperature, which are usually dependent upon the age and position of the ice sample. In general sea ice is rather constant at a specific gravity of 0.9, which results from the fact that if freezing rate increases more salt is trapped, thus increasing the density, but also more air is present, thus decreasing the density.. As the brine migrates down, there is a slight increase in density with depth.

Thermal and Electrical Properties of Ice

The temperature of sea ice varies with the depth of the ice and time of year. During winter the top of sea ice is about -20°C, and at the usual ice water interface the temperature is at the freezing point of seawater of about -2°C. During the summer the ice temperature becomes more uniform at -2°C to -8°C in the central Arctic basin, and 0°C to -1°C further south. Ice below a temperature of -23°C is harder, and somewhat brittle, but has more strength than ice of a higher temperature. There appear to be three zones of strength and ice color associated with the critical temperatures for the precipitation of salts. Ice below -23°C is grayish-white, probably because of the precipitat~~ed~~ion of sodium sulfate decahydrate at -8.2°C and sodium chloride dihydrate at -23°C. At temperatures above -23°C ice has a slight blue shade, and above -8°C ice is dark and wet. It appears that ice above -8°C has less bearing strength than ice at colder temperatures. The amount of heat required to melt one pound of freshwater ice is 120 B.T.U.; however, as the brine content increases the required heat decreases. Fresh water ice at -1.0°C requires 80 calories per gram to melt, but sea ice with a salt content of 8% requires only 4~~5~~9 calories.

The thermal conductivity is related to the salt content air bubble concentration, and temperature. For sea ice of

0.2% salt content at -1°C the value is 0.0055 calories/cm sec°C. For iceberg ice the thermal conductivity is .0053 calories/cm sec°C. The specific heat under the same conditions is 2.7 cal/gm°C. The diffusivity of pure ice (sp. heat at -2°C of 0.5) is 0.0115 cm^2/sec.

The infrared emissivity is 0.99 and the reflectivity for visible light is 0.85 for snow covered sea ice during winter, and 0.5 for ice and water puddles during summer.

The dielectric coefficient for iceberg ice is approximately 3.5, but for sea ice varies from 10,000 at frequencies of a few Hertz to about 10 at 50 Mhz.

ICE NAVIGATION AND HAZARDS TO SHIPPING

Ice Disasters

One of the earliest major sea disasters involving sea ice and icebergs occurred in 1777 when twelve vessels of the Dutch whaling fleet were caught in heavy ice off East Greenland and sank in the Denmark Strait. Probably the greatest loss prior to the Titanic disaster was the total loss of more than 50 American whaling ships during sudden Arctic "freezes" in the years 1871, 1876, 1888, and 1896. The greatest problem in navigating past the Grand Banks region, which is on the great circle route from North America and Europe, is limited visibility due to a low-lying fog, most persistent during the worst ice threat period of April, May and June. In fact, the Grand Banks region is the second foggiest area of the world. As shipping increased, the increasing frequency of pack ice and iceberg collisions seemed less of a threat than the risk of collisions between ships bound on opposite courses at night or in fog. After the collision between a French steamer VESTA and the American ship ARCTIC, which took 300 lives, separate eastbound and westbound lanes across the North Atlantic Ocean were prescribed. A further modification of recommended shipping lanes was instituted in 1898 because of the continued frequency of iceberg and pack ice collisions. Unfortunately icebergs wander astray of prescribed limits, and although shipping lanes were well established and honored by the big shipping companies, still collisions occurred.

After perhaps 3,000 years of snow accumulation and creeping across the Greenland subglacial terrain, an iceberg broke off on the West Greenland coast and drifted perhaps two years to April, 1912, when she found herself in the Labrador Current sailing at one to two knots toward the North Atlantic shipping routes. This iceberg had a ram (underwater projection) as most icebergs do by the time they enter the warmer waters near the Gulf Stream. Under control of wind and current, this iceberg drifted into the path of the TITANIC on 14 April 1912, and they collided in latitude 41°46'N, longitude 50°14'W with the loss of 1,513 lives. This tragedy resulted in the establishment of the International Ice Patrol in 1913 to patrol and guard by ship, plane or whatever means feasible the eastern, southern and western limits of drifting Arctic ice during the most dangerous part of the year. Ships are warned twice daily by detailed messages broadcast to all North Atlantic shipping concerning the boundaries of ice and position of dangerous icebergs. The U. S. Coast Guard has operated the ice patrol since 1913.

The most recent major iceberg tragedy occurred near the tip of Greenland out of the patrol area of the International Ice Patrol, but ironically just after the U. S. Coast Guard initiated an intensive reevaluation of the known poor ability of radar to detect icebergs. In January, 1959, the Danish icebreaking passenger cargo ship HANS HEDTOFT sank after colliding with an iceberg in heavy seas. Ninety-five passengers including dignitaries, experienced ice navigator, crew, modern radar equipment, and valuable historical documents were lost.

Icebreakers

Icebreakers are specially reinforced, high powered ships designed to break through both fresh water and sea ice in both the Arctic and Antarctic, and in inland regions such as New York's East River, the Delaware River and the St. Lawrence Seaway. Perhaps the first ship built especially to clear ice and assist movement of cargo ships in and out of harbors was the paddlewheel steamer used on the Delaware River in 1837. During the mid-fifties specially built or reinforced vessels were used in Sweden, Germany and Russia for both river ice and sea ice navigation. The first polar icebreaker was the Russian YERMAK, built in England in 1899. This ship has had more than fifty years sea Arctic service experience. During World War II the United States Coast Guard engineers designed and built the wind class ships, some of which, after being christened, were loaned to the Russians. More recently larger and more powerful icebreakers have been built, such as the Argentine's GENERAL SAN MARTIN and the United States icebreaker GLACIER. The Russian icebreakers of prominence are the MOSKVA, which is the most powerful conventionally propelled icebreaker, and the Russian first nuclear icebreaker LENIN, which has a nominal horse power of 44,000. The majority of the United States vessels of the wind class develop 10,000 horse power. The Canadian icebreaker CCGS LABRADOR, the work horse of the St. Lawrence Seaway is a Wind class ship. These vessels have been in service for more than 25 years, and represent the major task force of ice breaking capabilities for polar research and military operations. In addition a number of cargo ships from the military sea and transportation service, United States Navy, and even private concerns, e.g., the S. S. MANHATTAN, designed to carry oil through the Northwest Passage, have reinforced bows with designs somewhat similar to the bow design of the wind class breakers. These ships carry little cargo, primarily because the space is occupied by engines and ice navigation equipment. Icebreakers of the United States are now operated by the U. S. Coast Guard, and are used to clear river ice and fresh water ice of the Great Lakes; and Arctic and Antarctic research and resupply.

The progress of the ice reinforced vessel or an icebreaker through ice is dependent upon the power the ship commands and the concentration of the ice. Usually a six diesel electric engine vessel is operating on only four engines, because of breakdowns, repairs or overhauls, and in planning navigation escorting duties this is kept in mind. With the sea surface covered with approximately 50% of sea ice two feet thick, the speed might be up to seven knots. With more than 80% of the ice covered, the field covered with thick ice with some hummocky floes, the speed of progress might be reduced to three knots. In these situations the escort ship is following closely astern, and the procedure requires extreme degrees of alertness and skill in order to avoid collision. When it is necessary to back and ram ice, the icebreaker is backed away approximately the length of a football field (100 yards) and full power is applied which results in the ship reaching a speed of a few knots when hitting the ice edge. The ship is allowed to ride up over the ice with the continued application of full power, and the ice breaks by the force associated with the weight of the ship. The ship propellers are reversed, and the ship moves astern in preparation for the next ramming and riding up over the ice. In situations where the ice is either under great pressure or thicker than ten feet, the progress is extremely slow, in that only a few feet are gained on each charge. Icebreakers are equipped with heeling tanks, which allow them to rock back and forth. These are usually used to work the ship out of ice when the ship is so tightly held that all the power of the engines is not sufficient to break her loose.

The first successful commercial passage through the Northwest Passage was completed by the super-tanker S. S. MANHATTAN in 1969. This ship was 1,005 feet long, and can carry 115,000 tons of oil. The bow was shaped after the design of the U. S. Coast Guard Icebreaker Fleet.

Ice Forecasting and Reconnaissance

Both in the Arctic and Antarctic, sea ice reconnaissance and forecasts are conducted by a number of nations with the primary work done by the U. S. Navy either through the Fleet Weather Office or the Ice Forecasting Central of the U. S. Naval Oceanographic Center. The Ice Forecasting Central has for many years supported research and supply Arctic and Antarctic missions through ice reconnaissance and careful short and long range forecasting. Additional supportive reconnaissance and regional forecasts are provided by the Canadian Government and U. S. Coast Guard ships. Support is even received from commercial airplanes, which frequently spot lonely icebergs far from the area of usual occurrence.

Satellite photographs lack the resolution for day-to-day iceberg reconnaissance; however, these photographs do show the sea ice edge both in the Arctic and Antarctic. Ice navigation in the Antarctic is similar to navigation for logistic support of military and scientific expeditions in the Arctic. ~~and Antarctic.~~ The emphasis is on sea ice distribution and concentration rather than icebergs, which offer little problem to ships once in the ice pack.

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